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(54) Title: PARALLEL PROCESSOR ARCHITECTURE

(57) Abstract: A parallel hardware-based multithreaded processor is described. The processor includes a general purpose processor that coordinates system functions and a plurality of microengines that support multiple hardware threads. The processor also includes a memory control system that has a first memory controller that sorts memory references based on whether the memory references are directed to an even bank or an odd bank of memory and a second memory controller that optimizes memory references based upon whether the memory references are read references or write reference.

## PARALLEL PROCESSOR ARCHITECTURE

## BACKGROUND

This invention relates to parallel processors.

5       Parallel processing is an efficient form of  
information processing of concurrent events in a computing  
process. Parallel processing demands concurrent execution  
of many programs in a computer, in contrast to sequential  
processing. In the context of a parallel processor,  
10 parallelism involves doing more than one thing at the same  
time. Unlike a serial paradigm where all tasks are  
performed sequentially at a single station or a pipelined  
machine where tasks are performed at specialized stations,  
with parallel processing, a plurality of stations are  
15 provided with each capable of performing all tasks. That  
is, in general all or a plurality of the stations work  
simultaneously and independently on the same or common  
elements of a problem. Certain problems are suitable for  
solution by applying parallel processing.

20       Thus, types of computer processing include single  
instruction stream, single data stream, the conventional  
serial von Neumann computer in which there is a single  
stream of instructions. A second processing type is the  
single instruction stream, multiple data streams process  
25 (SIMD). This processing can have multiple arithmetic-logic  
processors and a single control processor. Each of the  
processors perform operations on the data in lock-step.  
These machines are synchronized by the control processor.  
A third type is multiple instruction streams, single data  
30 stream (MISD) process. This processing has the same data

stream flows through a linear array of processors executing different instruction streams. A fourth is multiple instruction streams, multiple data streams (MIMD). This processing uses multiple processors, each executing its own  
5 instruction stream to process a data stream fed to each of the processors. Multiple instruction streams, multiple data streams (MIMD) processors may have several instruction processing units and therefore several data streams.

10 SUMMARY

According to an aspect of the present invention, a parallel hardware-based multithreaded processor includes a general purpose processor that coordinates system functions and a plurality of microengines that support multiple  
15 hardware threads.

According to an additional aspect of the present invention, a parallel hardware-based multithreaded processor includes a general purpose processor that coordinates system functions and a plurality of  
20 microengines that support multiple hardware threads. The processor also includes a memory control system including a first memory controller that sorts memory references based on whether the memory references are directed to an even bank or an odd bank of memory and a second memory  
25 controller that optimizes memory references based upon whether the memory references are read references or write references.

One or more of the following advantages may be provided by one or more aspects of the invention.

This parallel multithreaded architecture provides a very general purpose microprocessor architecture. The processor can be connected to other devices to process large amounts of data. The system is especially useful for  
5 tasks that can be broken into parallel subtasks or functions. The hardware-based multithreaded processor is useful for tasks that are bandwidth oriented rather than latency oriented. The hardware-based multithreaded processor has multiple microengines each with multiple  
10 hardware controlled threads that can be simultaneously active and independently work on a task.

One example of an application for the hardware-based multithreaded processor is as a network processor. As a network processor, the hardware-based multithreaded  
15 processor can interfaces to network devices such as a media access controllers. As a network processor, the hardware-based multithreaded processor can interface to any type of communication device or interface that receives/sends large amounts of data. The processor can be used a print engine  
20 for a postscript processor or as a processor for a storage subsystem, i.e., RAID disk storage. A further use is as a matching engine. In the securities industry for example, the advent of electronic trading requires the use of electronic matching engines to match orders between buyers  
25 and sellers. These and other parallel types of tasks can be accomplished on the processor used in a system.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a communication system  
30 employing a hardware-based multithreaded processor.

FIG. 2 is a detailed block diagram of the hardware-based multithreaded processor of FIG. 1.

FIG. 3 is a block diagram of a microengine functional unit employed in the hardware-based multithreaded processor  
5 of FIGS. 1 and 2.

FIG. 3A is a block diagram of a pipeline in the microengine of FIG. 3.

FIG. 3B. is diagram that shows a format for a context switch instruction.

10 FIG. 3C is a block diagram showing general purpose register address arrangement.

FIG. 4 is a block diagram of a memory controller for enhanced bandwidth operation used in the hardware-based multithreaded processor.

15 FIG. 4A is a flow chart that represents an arbitration policy in an SDRAM controller of FIG. 4.

FIG. 4B is a timing diagram that shows advantages of optimizing SDRAM controller.

20 FIG. 5 is a block diagram of a memory controller for latency limited operations used in the hardware-based multithreaded processor.

FIG. 5A is a timing diagram that shows advantages of optimizing SRAM controller.

25 FIG. 6 is a block diagram of a communication bus interface in the processor of FIG. 1.

## DESCRIPTION

Architecture:

Referring to FIG. 1, a communication system 10 includes a parallel, hardware-based multithreaded processor 12. The hardware-based multithreaded processor 12 is coupled to a bus such as a PCI bus 14, a memory system 16 and a second bus 18. The system 10 is especially useful for tasks that can be broken into parallel subtasks or functions. Specifically hardware-based multithreaded processor 12 is useful for tasks that are bandwidth oriented rather than latency oriented. The hardware-based multithreaded processor 12 has multiple microengines 22 each with multiple hardware controlled threads that can be simultaneously active and independently work on a task.

The hardware-based multithreaded processor 12 also includes a central controller 20 that assists in loading microcode control for other resources of the hardware-based multithreaded processor 12 and performs other general purpose computer type functions such as handling protocols, exceptions, extra support for packet processing where the microengines pass the packets off for more detailed processing such as in boundary conditions. In one embodiment, the processor 20 is a Strong Arm<sup>®</sup> (Arm is a trademark of ARM Limited, United Kingdom) based architecture. The general purpose microprocessor 20 has an operating system. Through the operating system the processor 20 can call functions to operate on microengines 22a-22f. The processor 20 can use any supported operating system preferably a real time operating system. For the core processor implemented as a Strong Arm architecture,

operating systems such as, MicrosoftNT real-time, VXWorks and  $\mu$ CUS, a freeware operating system available over the Internet, can be used.

The hardware-based multithreaded processor 12 also  
5 includes a plurality of function microengines 22a-22f. Functional microengines (microengines) 22a-22f each maintain a plurality of program counters in hardware and states associated with the program counters. Effectively, a corresponding plurality of sets of threads can be  
10 simultaneously active on each of the microengines 22a-22f while only one is actually operating at any one time.

In one embodiment, there are six microengines 22a-22f as shown. Each microengines 22a-22f has capabilities for processing four hardware threads. The six microengines  
15 22a-22f operate with shared resources including memory system 16 and bus interfaces 24 and 28. The memory system 16 includes a Synchronous Dynamic Random Access Memory (SDRAM) controller 26a and a Static Random Access Memory (SRAM) controller 26b. SDRAM memory 16a and SDRAM  
20 controller 26a are typically used for processing large volumes of data, e.g., processing of network payloads from network packets. The SRAM controller 26b and SRAM memory 16b are used in a networking implementation for low latency, fast access tasks, e.g., accessing look-up tables,  
25 memory for the core processor 20, and so forth.

The six microengines 22a-22f access either the SDRAM 16a or SRAM 16b based on characteristics of the data. Thus, low latency, low bandwidth data is stored in and fetched from SRAM, whereas higher bandwidth data for which  
30 latency is not as important, is stored in and fetched from

SDRAM. The microengines 22a-22f can execute memory reference instructions to either the SDRAM controller 26a or SRAM controller 16b.

Advantages of hardware multithreading can be explained  
5 by SRAM or SDRAM memory accesses. As an example, an SRAM access requested by a Thread\_0, from a microengine will cause the SRAM controller 26b to initiate an access to the SRAM memory 16b. The SRAM controller controls arbitration for the SRAM bus, accesses the SRAM 16b, fetches the data  
10 from the SRAM 16b, and returns data to a requesting microengine 22a-22b. During an SRAM access, if the microengine e.g., 22a had only a single thread that could operate, that microengine would be dormant until data was returned from the SRAM. By employing hardware context  
15 swapping within each of the microengines 22a-22f, the hardware context swapping enables other contexts with unique program counters to execute in that same microengine. Thus, another thread e.g., Thread\_1 can function while the first thread, e.g., Thread\_0, is  
20 awaiting the read data to return. During execution, Thread\_1 may access the SDRAM memory 16a. While Thread\_1 operates on the SDRAM unit, and Thread\_0 is operating on the SRAM unit, a new thread, e.g., Thread\_2 can now operate in the microengine 22a. Thread\_2 can operate for a certain  
25 amount of time until it needs to access memory or perform some other long latency operation, such as making an access to a bus interface. Therefore, simultaneously, the processor 12 can have a bus operation, SRAM operation and SDRAM operation all being completed or operated upon by one  
30 microengine 22a and have one more thread available to



process more work in the data path.

The hardware context swapping also synchronizes completion of tasks. For example, two threads could hit the same shared resource e.g., SRAM. Each one of these  
5 separate functional units, e.g., the FBUS interface 28, the SRAM controller 26a, and the SDRAM controller 26b, when they complete a requested task from one of the microengine thread contexts reports back a flag signaling completion of an operation. When the flag is received by the  
10 microengine, the microengine can determine which thread to turn on.

One example of an application for the hardware-based multithreaded processor 12 is as a network processor. As a network processor, the hardware-based multithreaded  
15 processor 12 interfaces to network devices such as a media access controller device e.g., a 10/100BaseT Octal MAC 13a or a Gigabit Ethernet device 13b. In general, as a network processor, the hardware-based multithreaded processor 12 can interface to any type of communication device or  
20 interface that receives/sends large amounts of data. Communication system 10 functioning in a networking application could receive a plurality of network packets from the devices 13a, 13b and process those packets in a parallel manner. With the hardware-based multithreaded  
25 processor 12, each network packet can be independently processed.

Another example for use of processor 12 is a print engine for a postscript processor or as a processor for a storage subsystem, i.e., RAID disk storage. A further use  
30 is as a matching engine. In the securities industry for

example, the advent of electronic trading requires the use of electronic matching engines to match orders between buyers and sellers. These and other parallel types of tasks can be accomplished on the system 10.

5       The processor 12 includes a bus interface 28 that couples the processor to the second bus 18. Bus interface 28 in one embodiment couples the processor 12 to the so-called FBUS 18 (FIFO bus). The FBUS interface 28 is responsible for controlling and interfacing the processor  
10   12 to the FBUS 18. The FBUS 18 is a 64-bit wide FIFO bus, used to interface to Media Access Controller (MAC) devices.

      The processor 12 includes a second interface e.g., a PCI bus interface 24 that couples other system components that reside on the PCI 14 bus to the processor 12. The PCI  
15   bus interface 24, provides a high speed data path 24a to memory 16 e.g., the SDRAM memory 16a. Through that path data can be moved quickly from the SDRAM 16a through the PCI bus 14, via direct memory access (DMA) transfers. The hardware based multithreaded processor 12 supports image  
20   transfers. The hardware based multithreaded processor 12 can employ a plurality of DMA channels so if one target of a DMA transfer is busy, another one of the DMA channels can take over the PCI bus to deliver information to another target to maintain high processor 12 efficiency.

25       Additionally, the PCI bus interface 24 supports target and master operations. Target operations are operations where slave devices on bus 14 access SDRAMs through reads and writes that are serviced as a slave to target operation. In master operations, the processor core 20  
30   sends data directly to or receives data directly from the

PCI interface 24.

Each of the functional units are coupled to one or more internal buses. As described below, the internal buses are dual, 32 bit buses (i.e., one bus for read and one for write). The hardware-based multithreaded processor 12 also is constructed such that the sum of the bandwidths of the internal buses in the processor 12 exceed the bandwidth of external buses coupled to the processor 12. The processor 12 includes an internal core processor bus 32, e.g., an ASB bus (Advanced System Bus) that couples the processor core 20 to the memory controller 26a, 26c and to an ASB translator 30 described below. The ASB bus is a subset of the so called AMBA bus that is used with the Strong Arm processor core. The processor 12 also includes a private bus 34 that couples the microengine units to SRAM controller 26b, ASB translator 30 and FBUS interface 28. A memory bus 38 couples the memory controller 26a, 26b to the bus interfaces 24 and 28 and memory system 16 including flashrom 16c used for boot operations and so forth.

Referring to FIG. 2, each of the microengines 22a-22f includes an arbiter that examines flags to determine the available threads to be operated upon. Any thread from any of the microengines 22a-22f can access the SDRAM controller 26a, SDRAM controller 26b or FBUS interface 28. The memory controllers 26a and 26b each include a plurality of queues to store outstanding memory reference requests. The queues either maintain order of memory references or arrange memory references to optimize memory bandwidth. For example, if a thread<sub>0</sub> has no dependencies or relationship to a thread<sub>1</sub>, there is no reason that thread 1 and 0

cannot complete their memory references to the SRAM unit out of order. The microengines 22a-22f issue memory reference requests to the memory controllers 26a and 26b. The microengines 22a-22f flood the memory subsystems 26a and 26b with enough memory reference operations such that the memory subsystems 26a and 26b become the bottleneck for processor 12 operation.

If the memory subsystem 16 is flooded with memory requests that are independent in nature, the processor 12 can perform memory reference sorting. Memory reference sorting improves achievable memory bandwidth. Memory reference sorting, as described below, reduces dead time or a bubble that occurs with accesses to SRAM. With memory references to SRAM, switching current direction on signal lines between reads and writes produces a bubble or a dead time waiting for current to settle on conductors coupling the SRAM 16b to the SRAM controller 26b.

That is, the drivers that drive current on the bus need to settle out prior to changing states. Thus, repetitive cycles of a read followed by a write can degrade peak bandwidth. Memory reference sorting allows the processor 12 to organize references to memory such that long strings of reads can be followed by long strings of writes. This can be used to minimize dead time in the pipeline to effectively achieve closer to maximum available bandwidth. Reference sorting helps maintain parallel hardware context threads. On the SDRAM, reference sorting allows hiding of pre-charges from one bank to another bank. Specifically, if the memory system 16b is organized into an odd bank and an even bank, while the processor is operating

on the odd bank, the memory controller can start precharging the even bank. Precharging is possible if memory references alternate between odd and even banks. By ordering memory references to alternate accesses to  
5 opposite banks, the processor 12 improves SDRAM bandwidth. Additionally, other optimizations can be used. For example, merging optimizations where operations that can be merged, are merged prior to memory access, open page optimizations where by examining addresses an opened page  
10 of memory is not reopened, chaining, as will be described below, and refreshing mechanisms, can be employed.

The FBUS interface 28 supports Transmit and Receive flags for each port that a MAC device supports, along with an Interrupt flag indicating when service is warranted.  
15 The FBUS interface 28 also includes a controller 28a that performs header processing of incoming packets from the FBUS 18. The controller 28a extracts the packet headers and performs a microprogrammable source/destination/protocol hashed lookup (used for address  
20 smoothing) in SRAM. If the hash does not successfully resolve, the packet header is sent to the processor core 20 for additional processing. The FBUS interface 28 supports the following internal data transactions:

FBUS unit Shared bus SRAM) to/from microengine.  
FBUS unit (via private bus) writes from SDRAM Unit.  
FBUS unit (via Mbus) Reads to SDRAM.

The FBUS 18 is a standard industry bus and includes a  
5 data bus, e.g., 64 bits wide and sideband control for  
address and read/write control. The FBUS interface 28  
provides the ability to input large amounts of data using a  
series of input and output FIFO's 29a-29b. From the FIFOs  
29a-29b, the microengines 22a-22f fetch data from or  
10 command the SDRAM controller 26a to move data from a  
receive FIFO in which data has come from a device on bus  
18, into the FBUS interface 28. The data can be sent  
through memory controller 26a to SDRAM memory 16a, via a  
direct memory access. Similarly, the microengines can move  
15 data from the SDRAM 26a to interface 28, out to FBUS 18,  
via the FBUS interface 28.

Data functions are distributed amongst the microengines. Connectivity to the SRAM 26a, SDRAM 26b and FBUS 28 is via command requests. A command request can be a memory request or a FBUS request. For example, a  
5 command request can move data from a register located in a microengine 22a to a shared resource, e.g., an SDRAM location, SRAM location, flash memory or some MAC address. The commands are sent out to each of the functional units and the shared resources. However, the shared resources do  
10 not need to maintain local buffering of the data. Rather, the shared resources access distributed data located inside of the microengines. This enables microengines 22a-22f, to have local access to data rather than arbitrating for access on a bus and risk contention for the bus. With this  
15 feature, there is a 0 cycle stall for waiting for data internal to the microengines 22a-22f.

The data buses, e.g., ASB bus 30, SRAM bus 34 and SDRAM bus 38 coupling these shared resources, e.g., memory controllers 26a and 26b are of sufficient bandwidth such  
20 that there are no internal bottlenecks. Thus, in order to avoid bottlenecks, the processor 12 has an bandwidth requirement where each of the functional units is provided with at least twice the maximum bandwidth of the internal buses. As an example, the SDRAM can run a 64 bit wide bus  
25 at 83 MHz. The SRAM data bus could have separate read and write buses, e.g., could be a read bus of 32 bits wide running at 166 MHz and a write bus of 32 bits wide at 166 MHz. That is, in essence, 64 bits running at 166 MHz which is effectively twice the bandwidth of the SDRAM.

The core processor 20 also can access the shared resources. The core processor 20 has a direct communication to the SDRAM controller 26a to the bus interface 24 and to SRAM controller 26b via bus 32.

5 However, to access the microengines 22a-22f and transfer registers located at any of the microengines 22a-22f, the core processor 20 access the microengines 22a-22f via the ASB Translator 30 over bus 34. The ASB translator 30 can physically reside in the FBUS interface 28, but logically  
10 is distinct. The ASB Translator 30 performs an address translation between FBUS microengine transfer register locations and core processor addresses (i.e., ASB bus) so that the core processor 20 can access registers belonging to the microengines 22a-22c.

15 Although microengines 22 can use the register set to exchange data as described below, a scratchpad memory 27 is also provided to permit microengines to write data out to the memory for other microengines to read. The scratchpad 27 is coupled to bus 34.



The processor core 20 includes a RISC core 50 implemented in a five stage pipeline performing a single cycle shift of one operand or two operands in a single cycle, provides multiplication support and 32 bit barrel shift support. This RISC core 50 is a standard Strong Arm® architecture but it is implemented with a five stage pipeline for performance reasons. The processor core 20 also includes a 16 kilobyte instruction cache 52, an 8 kilobyte data cache 54 and a prefetch stream buffer 56.

The core processor 20 performs arithmetic operations in parallel with memory writes and instruction fetches. The core processor 20 interfaces with other functional units via the ARM defined ASB bus. The ASB bus is a 32-bit bi-directional bus 32.

15

#### Microengines:

Referring to FIG. 3, an exemplary one of the microengines 22a-22f, e.g., microengine 22f is shown. The microengine includes a control store 70 which, in one implementation, includes a RAM of here 1,024 words of 32 bit. The RAM stores a microprogram. The microprogram is loadable by the core processor 20. The microengine 22f also includes controller logic 72. The controller logic includes an instruction decoder 73 and program counter (PC) units 72a-72d. The four micro program counters 72a-72d are maintained in hardware. The microengine 22f also includes context event switching logic 74. Context event logic 74 receives messages (e.g., SEQ\_#\_EVENT\_RESPONSE; FBI\_EVENT\_RESPONSE; SRAM \_EVENT\_RESPONSE; SDRAM

\_EVENT\_RESPONSE; and ASB \_EVENT\_RESPONSE) from each one of

30

the shared resources, e.g., SRAM 26a, SDRAM 26b, or processor core 20, control and status registers, and so forth. These messages provide information on whether a requested function has completed. Based on whether or not a function requested by a thread has completed and signaled completion, the thread needs to wait for that completion signal, and if the thread is enabled to operate, then the thread is placed on an available thread list (not shown). The microengine 22f can have a maximum of e.g., 4 threads available.

In addition to event signals that are local to an executing thread, the microengines 22 employ signaling states that are global. With signaling states, an executing thread can broadcast a signal state to all microengines 22. Receive Request Available signal, Any and all threads in the microengines can branch on these signaling states. These signaling states can be used to determine availability of a resource or whether a resource is due for servicing.

The context event logic 74 has arbitration for the four (4) threads. In one embodiment, the arbitration is a round robin mechanism. Other techniques could be used including priority queuing or weighted fair queuing. The microengine 22f also includes an execution box (EBOX) data path 76 that includes an arithmetic logic unit 76a and general purpose register set 76b. The arithmetic logic unit 76a performs arithmetic and logical functions as well as shift functions. The registers set 76b has a relatively large number of general purpose registers. As will be described in FIG. 3B, in this implementation there are 64

general purpose registers in a first bank, Bank A and 64 in a second bank, Bank B. The general purpose registers are windowed as will be described so that they are relatively and absolutely addressable.

5       The microengine 22f also includes a write transfer register stack 78 and a read transfer stack 80. These registers are also windowed so that they are relatively and absolutely addressable. Write transfer register stack 78 is where write data to a resource is located. Similarly,  
10   read register stack 80 is for return data from a shared resource. Subsequent to or concurrent with data arrival, an event signal from the respective shared resource e.g., the SRAM controller 26a, SDRAM controller 26b or core processor 20 will be provided to context event arbiter 74  
15   which will then alert the thread that the data is available or has been sent. Both transfer register banks 78 and 80 are connected to the execution box (EBOX) 76 through a data path. In one implementation, the read transfer register has 64 registers and the write transfer register has 64  
20   registers.

As shown in FIG. 3A, the microengine datapath maintains a 5-stage micro-pipeline 82. This pipeline includes lookup of microinstruction words 82a, formation of the register file addresses 82b, read of operands from  
25   register file 82c, ALU, shift or compare operations 82d, and write-back of results to registers 82e. By providing a write-back data bypass into the ALU/shifter units, and by assuming the registers are implemented as a register file (rather than a RAM), the microengine can perform a  
30   simultaneous register file read and write, which completely

hides the write operation.

The SDRAM interface 26a provides a signal back to the requesting microengine on reads that indicates whether a parity error occurred on the read request. The microengine

5 microcode is responsible for checking the SDRAM read Parity flag when the microengine uses any return data. Upon checking the flag, if it was set, the act of branching on it clears it. The Parity flag is only sent when the SDRAM is enabled for checking, and the SDRAM is parity protected.

10 The microengines and the PCI Unit are the only requestors notified of parity errors. Therefore, if the processor core 20 or FIFO requires parity protection, a microengine assists in the request. The microengines 22a-22f support conditional branches. The worst case conditional branch

15 latency (not including jumps) occurs when the branch decision is a result of condition codes being set by the previous microcontrol instruction. The latency is shown below in Table 1:

		1	2	3	4	5	6	7	8
	-----+-----+-----+-----+-----+-----+-----+-----+								
	microstore lookup	n1	cb	n2	XX	b1	b2	b3	
	b4								
5	reg addr gen		n1	cb	XX	XX	b1	b2	b3
	reg file lookup			n1	cb	XX	XX	b1	b2
	ALU/shifter/cc				n1	cb	XX	XX	b1
	write back			m2		n1	cb	XX	XX

- 10                where nx is pre-branch microword (n1 sets cc's)  
                   cb is conditional branch  
                   bx is post-branch microword  
                   XX is aborted microword

As shown in Table 1, it is not until cycle 4 that the  
 15 condition codes of n1 are set, and the branch decision can  
 be made (which in this case causes the branch path to be  
 looked up in cycle 5). The microengine incurs a 2-cycle  
 branch latency penalty because it must abort operations n2  
 and n3 (the 2 microwords directly after the branch) in the  
 20 pipe, before the branch path begins to fill the pipe with  
 operation b1. If the branch is not taken, no microwords  
 are aborted and execution continues normally. The  
 microengines have several mechanisms to reduce or eliminate  
 the effective branch latency.

The microengines support deferred branches. Deferring branches are when a microengine allows 1 or 2 microwords after the branch to occur before the branch takes effect (i.e. the effect of the branch is "deferred" in time).

- 5 Thus, if useful work can be found to fill the wasted cycles after the branch microword, then the branch latency can be hidden. A 1-cycle deferred branch is shown below where n2 is allowed to execute after cb, but before b1:

10

		1	2	3	4	5	6	7	8
	-----+-----+-----+-----+-----+-----+-----+-----								
	microstore lookup	n1	cb	n2	XX	b1	b2	b3	
	b4								
15	reg addr gen		n1	cb	n2	XX	b1	b2	b3
	reg file lookup			n1	cb	n2	XX	b1	b2
	ALU/shifter/cc				n1	cb	n2	XX	b1
	write back					n1	cb	n2	XX

- 20 A 2-cycle deferred branch is shown below, where n2 and n3 are both allowed to complete before the branch to b1 occurs. Note that a 2-cycle branch deferment is only allowed when the condition codes are set on the microword preceding the branch.

25

		1	2	3	4	5	6	7	8	9
	-----+-----+-----+-----+-----+-----+-----+-----									
	microstore lookup	n1	cb	n2	n3	b1	b2	b3	b4	b5
	reg addr gen		n1	cb	n2	n3	b1	b2	b3	b4
30	reg file lkup			n1	cb	n2	n3	b1	b2	b3
	ALU/shftr/cc				n1	cb	n2	n3	b1	b2
	write back					n1	cb	n2	n3	b1

The microengines also support condition code evaluation. If the condition codes upon which a branch decision are made are set 2 or more microwords before the branch, then 1 cycle of branch latency can be eliminated because the branch decision can be made 1 cycle earlier:

		1	2	3	4	5	6	7	8
		-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+
microstore lookup		n1	n2	cb	XX	b1	b2	b3	b4
10 reg addr gen			n1	n2	cb	XX	b1	b2	b3
reg file lookup				n1	n2	cb	XX	b1	b2
ALU/shifter/cc					n1	n2	cb	XX	b1
write back						n1	n2	cb	XX

15 In this example, n1 sets the condition codes and n2 does not set the conditions codes. Therefore, the branch decision can be made at cycle 4 (rather than 5), to eliminate 1 cycle of branch latency. In the example below, the 1-cycle branch deferment and early setting of condition codes are combined to completely hide the branch latency:

Condition codes (cc's) set 2 cycles before a 1-cycle deferred branch:

		1	2	3	4	5	6	7	8
		-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+
microstore lookup		n1	n2	cb	n3	b1	b2	b3	b4
reg addr gen			n1	n2	cb	n3	b1	b2	b3
reg file lookup				n1	n2	cb	n3	b1	b2
30 ALU/shifter/cc					n1	n2	cb	n3	b1
write back						n1	n2	cb	n3

In the case where the condition codes cannot be set early (i.e. they are set in the microword preceding the branch), the microengine supports branch guessing which attempts to reduce the 1 cycle of exposed branch latency that remains. By "guessing" the branch path or the sequential path, the microsequencer pre-fetches the guessed path 1 cycle before it definitely knows what path to execute. If it guessed correctly, 1 cycle of branch latency is eliminated as shown below:

10

guess branch taken /branch is taken

		1	2	3	4	5	6	7	8
15	microstore lookup	n1	cb	n1	b1	b2	b3	b4	b5
	reg addr gen		n1	cb	XX	b1	b2	b3	b4
	reg file lookup			n1	cb	XX	b1	b2	b3
	ALU/shifter/cc				n1	cb	XX	b1	b2
	write back					n1	cb	XX	b1

20

If the microcode guessed a branch taken incorrectly, the microengine still only wastes 1 cycle:



guess branch taken /branch is NOT taken

		1	2	3	4	5	6	7	8
		-----+-----+-----+-----+-----+-----+-----+-----							
5	microstore lookup	n1	cb	n1	XX	n2	n3	n4	n5
	reg addr gen		n1	cb	n1	XX	n2	n3	n4
	reg file lookup			n1	cb	n1	XX	n2	n3
	ALU/shifter/cc				n1	cb	n1	XX	n2
	write back					n1	cb	n1	XX

10

However, the latency penalty is distributed differently when microcode guesses a branch is not taken:

For guess branch NOT taken / branch is NOT taken there are no wasted cycles as set out below.

15

		1	2	3	4	5	6	7	8
		-----+-----+-----+-----+-----+-----+-----+-----							
	microstore lookup	n1	cb	n1	n2	n3	n4	n5	n6
	reg addr gen		n1	cb	n1	n2	n3	n4	n5
20	reg file lookup			n1	cb	n1	n2	n1	b4
	ALU/shifter/cc				n1	cb	n1	n2	n3
	write back					n1	cb	n1	n2

However for guess branch NOT taken /branch is taken  
25 there are 2 wasted cycles.

			1	2	3	4	5	6	7	8								
	-----+-----+-----+-----+-----+-----+-----+-----+-----																	
30	microstore lookup		n1		cb		n1		XX		b1		b2		b3			
	b4																	
	reg addr gen				n1		cb		XX		XX		b1		b2		b3	
	reg file lookup						n1		cb		XX		XX		b1		b2	
	ALU/shifter/cc						n1		cb		XX		XX		b1			
35	write back								n1		cb		XX		XX			

The microengine can combine branch guessing with 1-cycle branch deferment to improve the result further. For guess branch taken with 1-cycle deferred branch/branch is taken

5 is:

		1	2	3	4	5	6	7	8									
		-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+									
	microstore lookup		n1		cb		n2		b1		b2		b3		b4		b5	
10	reg addr gen				n1		cb		n2		b1		b2		b3		b4	
	reg file lookup						n1		cb		n2		b1		b2		b3	
	ALU/shifter/cc								n1		cb		n2		b1		b2	
	write back										n1		cb		n2		b1	

15

In the case above, the 2 cycles of branch latency are hidden by the execution of n2, and by correctly guessing the branch direction. If microcode guesses incorrectly, 1 cycle of branch latency remains exposed as shown below:

20

guess branch taken with 1-cycle deferred branch/branch is  
NOT taken

		1	2	3	4	5	6	7	8	9	
25		-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+	
	microstore lookup	n1	cb	n2	XX	n3	n4	n5	n6	n7	
	reg addr gen		n1	cb	n2	XX	n3	n4	n5	n6	
	reg file lkup			n1	cb	n2	XX	n3	n4	n5	
	ALU/shftr/cc				n1	cb	n2	XX	n3	n4	
30	write back					n1	cb	n2	XX	n3	

If microcode correctly guesses a branch NOT taken, then the pipeline flows sequentially in the normal unperturbed case. If microcode incorrectly guesses branch NOT taken, the microengine again exposes 1 cycle of  
 5 unproductive execution as shown below:

guess branch NOT taken/branch is taken

		1	2	3	4	5	6	7	8	9
10	microstore lookup	n1	cb	n2	XX	b1	b2	b3	b4	b5
	reg addr gen		n1	cb	n2	XX	b1	b2	b3	b4
	reg file lkup			n1	cb	n2	XX	b1	b2	b3
	ALU/shftr/cc				n1	cb	n2	XX	b1	b2
15	write back					n1	cb	n2	XX	b1

where nx is pre-branch microword (n1 sets cc's)

cb is conditional branch

bx is post-branch microword

XX is aborted microword

20 In the case of a jump instruction, 3 extra cycles of latency are incurred because the branch address is not known until the end of the cycle in which the jump is in the ALU stage:

		1	2	3	4	5	6	7	8	9
25	microstore lookup	n1	jp	XX	XX	XX	j1	j2	j3	j4
	reg addr gen		n1	jp	XX	XX	XX	j1	j2	j3
30	reg file lkup			n1	jp	XX	XX	XX	j1	j2
	ALU/shftr/cc				n1	jp	XX	XX	XX	j1
	write back					n1	jp	XX	XX	XX

## Context Switch:

Referring to FIG. 3B, a format from a context switch instruction is shown. A context switch is a special form of a branch that causes a different context (and associated PC) to be selected. Context switching introduces some branch latency as well. Consider the following context switch:

```

10      | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
      -----+-----+-----+-----+-----+-----+-----+-----+
microstore lookup | ol | ca | br | n1 | n2 | n3 | n4 | n5 | n6 |
reg addr gen    |   | ol | ca | XX | n1 | n2 | n3 | n4 | n5 |
reg file lkup   |   |   | ol | ca | XX | n1 | n2 | n3 | n4 |
15  ALU/shftr/cc |   |   |   | ol | ca | XX | n1 | n2 | n3 |
write back      |   |   |   |   | ol | ca | XX | n1 | n2 |

```

where ox is old context flow

br is branch microword in old context

20 ca is context rearbitration (causes context switch)

nx is new context flow

XX is aborted microword

In a context switch the "br" microword is aborted to avoid control and timing complexities that could be caused by saving the correct old context PC.

Conditional branches that operate on ALU condition codes which are set on the microword before the branch can select 0, 1 or 2-cycle branch deferment modes. Condition codes set 2 or more microwords before the conditional branch that operates on them can select 0 or 1-cycle branch deferment modes. All other branches (including context rearbitrations) can select either 0 or 1-cycle branch

deferment modes. The architecture could be designed to make a context arbitration microword within a branch deferment window of a preceding branch, jump or context arbitration microword, an illegal option. That is, in some  
5 embodiments, a context switch would not be allowed to occur during a branch transition in the pipeline because as mentioned, it could unduly complicate saving of the old context PC. The architecture could also be designed to make branching within the branch deferment window of a  
10 preceding branch, jump or context arbitration microword illegal to avoid complicated and possible unpredictable branch behaviors.

Each microengine 22a-22f supports multi-threaded execution of four contexts. One reason for this is to  
15 allow one thread to start executing just after another thread issues a memory reference and must wait until that reference completes before doing more work. This behavior is critical to maintaining efficient hardware execution of the microengines because memory latency is significant.  
20 Stated differently, if only a single thread execution was supported, the microengines would sit idle for a significant number of cycles waiting for references to return and thereby reduce overall computational throughput. Multi-threaded execution allows an microengines to hide  
25 memory latency by performing useful independent work across several threads. Two synchronization mechanisms are supplied in order to allow a thread to issue an SRAM or SDRAM reference, and then subsequently synchronize to the point in time when that reference completes.

One mechanism is Immediate Synchronization. In immediate synchronization, the microengine issues the reference and immediately swap out that context. The context will be signaled when the corresponding reference  
5 completes. Once signaled, the context will be swapped back in for execution when a context-swap event occurs and it is its turn to run. Thus, from the point of view of a single context's instruction stream, the microword after issuing the mem reference does not get executed until the reference  
10 completes.

A second mechanism is Delayed Synchronization. In delayed synchronization, the microengine issues the reference, and then continues to execute some other useful work independent of the reference. Some time later it  
15 could become necessary to synchronize the thread's execution stream to the completion of the issued reference before further work is performed. At this point a synchronizing microword is executed that will either swap out the current thread, and swap it back in sometime later  
20 when the reference has completed, or continue executing the current thread because the reference has already completed. Delayed synchronization is implemented using two different signaling schemes:

If the memory reference is associated with a transfer  
25 register, the signal from which the thread is triggered is generated when the corresponding transfer register valid bit is set or cleared. For example, an SRAM read which deposits data into transfer register A would be signaled when the valid bit for A is set. If the memory reference  
30 is associated with the transfer FIFO or the receive FIFO,

instead of a transfer register, then the signal is generated when the reference completes in the SDRAM controller 26a. Only one signal state per context is held in the microengines scheduler, thus only one outstanding  
5 signal can exist in this scheme.

There are at least two general operational paradigms from which microcontroller micro-programs could be designed. One would be that overall microcontroller compute throughput and overall memory bandwidth are  
10 optimized at the expense of single thread execution latency. This paradigm would make sense when the system has multiple microengines executing multiple threads per microengine on unrelated data packets.

A second one is that microengine execution latency  
15 should be optimized at the expense of overall microengine compute throughput and overall memory bandwidth. This paradigm could involve execution of a thread with a real-time constraint, that is, a constraint which dictates that some work must absolutely be done by some specified time.  
20 Such a constraint requires that optimization of the single thread execution be given priority over other considerations such as memory bandwidth or overall computational throughput. A real-time thread would imply a single microengine that executes only one thread.  
25 Multiple threads would not be handled because the goal is to allow the single real-time thread to execute as soon as possible--execution of multiple threads would hinder this ability.

The coding style of these two paradigms could be  
30 significantly different with regard to issuing memory

references and context switching. In the real time case, the goal is to issue as many memory references as soon as possible in order to minimize the memory latency incurred by those references. Having issued as many references as  
5 early as possible the goal would be to perform as many computations as the microengines as possible in parallel with the references. A computation flow that corresponds to real-time optimization is:

- 10      o) issue mem ref 1
- o) issue mem ref 2
- o) issue mem ref 3
- o) perform work independent of mem refs 1, 2 and 3
- o) synch to completion of mem ref 1
- 15      o) perform work dependent on mem ref 1 and independent of mem ref 2  
         and 3
- o) issue any new mem refs based on preceding work.
- o) synch to completion of mem ref 2
- o) perform work dependent on mem ref 1 and 2 independent of mem ref
- 20      3
- o) issue any new mem refs based on preceding work.
- o) synch to completion of mem ref 3
- o) perform work dependent on the completion of all 3 refs
- o) issue any new mem refs based on preceding work.

25

In contrast, optimization for throughput and bandwidth would take a different approach. With optimization for microengine computational throughput and overall memory bandwidth less consideration is given to single thread  
30 execution latency. To accomplish this, the goal would be to equally space memory references across the microprogram for each thread. This would provide a uniform stream of memory references to the SRAM and SDRAM controllers and



would maximize the probability that 1 thread is always available to hide the memory latency incurred when another thread is swapped out.

5   Register file address types:

Referring to FIG. 3C, the two register address spaces that exist are Locally accessible registers, and Globally accessible registers accessible by all microengines. The General Purpose Registers (GPRs) are implemented as two  
10   separate banks (A bank and B bank) whose addresses are interleaved on a word-by-word basis such that A bank registers have lsb=0, and B bank registers have lsb=1. Each bank is capable of performing a simultaneous read and write to two different words within its bank.

15       Across banks A and B, the register set 76b is also organized into four windows 76b<sub>0</sub>-76b<sub>3</sub> of 32 registers that are relatively addressable per thread. Thus, thread\_0 will find its register 0 at 77a (register 0), the thread\_1 will find its register\_0 at 77b (register 32), thread\_2 will  
20   find its register\_0 at 77c (register 64), and thread\_3 at 77d (register 96). Relative addressing is supported so that multiple threads can use the exact same control store and locations but access different windows of register and perform different functions. The uses of register window  
25   addressing and bank addressing provide the requisite read bandwidth using only dual ported RAMS in the microengine 22f.

These windowed registers do not have to save data from context switch to context switch so that the normal push  
30   and pop of a context swap file or stack is eliminated.

Context switching here has a 0 cycle overhead for changing from one context to another. Relative register addressing divides the register banks into windows across the address width of the general purpose register set. Relative

5 addressing allows access any of the windows relative to the starting point of the window. Absolute addressing is also supported in this architecture where any one of the absolute registers may be accessed by any of the threads by providing the exact address of the register.

10 Addressing of general purpose registers 78 can occur in 2 modes depending on the microword format. The two modes are absolute and relative. In absolute mode, addressing of a register address is directly specified in 7-bit source field (a6-a0 or b6-b0):

15

	7	6	5	4	3	2	1	0	
	+---+---+---+---+---+---+---+---+								
A GPR:	a6	0	a5	a4	a3	a2	a1	a0	a6=0
B GPR:	b6	1	b5	b4	b3	b2	b1	b0	b6=0
20 SRAM/ASB:	a6	a5	a4	0	a3	a2	a1	a0	a6=1, a5=0, a4=0
SDRAM:	a6	a5	a4	0	a3	a2	a1	a0	a6=1, a5=0, a4=1

register address directly specified in 8-bit dest field (d7-d0):

25

	7	6	5	4	3	2	1	0	
	+---+---+---+---+---+---+---+---+								
A GPR:	d7	d6	d5	d4	d3	d2	d1	d0	d7=0, d6=0
B GPR:	d7	d6	d5	d4	d3	d2	d1	d0	d7=0, d6=1
30 SRAM/ASB:	d7	d6	d5	d4	d3	d2	d1	d0	d7=1, d6=0, d5=0
SDRAM:	d7	d6	d5	d4	d3	d2	d1	d0	d7=1, d6=0, d5=1

If  $\langle a6:a5 \rangle = 1,1$ ,  $\langle b6:b5 \rangle = 1,1$ , or  $\langle d7:d6 \rangle = 1,1$  then the lower bits are interpreted as a context-relative address field (described below). When a non-relative A or B source address is specified in the A, B absolute field, only the lower half of the SRAM/ASB and SDRAM address spaces can be addressed. Effectively, reading absolute SRAM/SDRAM devices has the effective address space; however, since this restriction does not apply to the dest field, writing the SRAM/SDRAM still uses the full address space.

10 In relative mode, addresses a specified address is offset within context space as defined by a 5-bit source field ( $a4-a0$  or  $b4-b0$ ):

		7	6	5	4	3	2	1	0	
		+-----+-----+-----+-----+-----+								
15	A GPR:	a4	0	context	a3	a2	a1	a0	a4=0	
	B GPR:	b4	1	context	b3	b2	b1	b0	b4=0	
	SRAM/ASB:	ab4	0	ab3  context	b2	b1	ab0	ab4=1, ab3=0		
	SDRAM:	ab4	0	ab3  context	b2	b1	ab0	ab4=1, ab3=1		

20 or as defined by the 6-bit dest field ( $d5-d0$ ):

		7	6	5	4	3	2	1	0	
		+-----+-----+-----+-----+-----+								
	A GPR:	d5	d4  context	d3	d2	d1	d0	d5=0, d4=0		
25	B GPR:	d5	d4  context	d3	d2	d1	d0	d5=0, d4=1		
	SRAM/ASB:	d5	d4  d3  context	d2	d1	d0	d5=1, d4=0, d3=0			
	SDRAM:	d5	d4  d3  context	d2	d1	d0	d5=1, d4=0, d3=1			

30 If  $\langle d5:d4 \rangle = 1,1$ , then the destination address does not address a valid register, thus, no dest operand is written back.

The following registers are globally accessible from the microengines and the memory controllers:

hash unit registers  
scratchpad and common registers  
5 receive FIFO and receive status FIFO  
transmit FIFO  
transmit control FIFO

The microengines are not interrupt driven. Each microflow executes until completion and then a new flow is chosen  
10 based on state signaled by other devices in the processor  
12.

Referring to FIG. 4, the SDRAM memory controller 26a includes memory reference queues 90 where memory reference requests arrive from the  
15 various microengines 22a-22f. The memory controller 26a includes an arbiter 91 that selects the next the microengine reference requests to go to any of the functioning units. Given that one of the microengines is providing a reference request, the reference request will  
20 come through the address and command queue 90, inside the SDRAM controller 26a. If the reference request has a bit set called the "optimized MEM bit" the incoming reference request will be sorted into either the even bank queue 90a or the odd bank queue 90b. If the memory reference request  
25 does not have a memory optimization bit set, the default will be to go into an order queue 90c. The SDRAM controller 26 is a resource which is shared among the FBUS interface 28, the core processor 20 and the PCI interface 24. The SDRAM controller 26 also maintains a state machine  
30 for performing READ-MODIFY-Write atomic operations. The

SDRAM controller 26 also performs byte alignment for requests of data from SDRAM.

The order queue 90c maintains the order of reference requests from the microengines. With a series of odd and even banks references it may be required that a signal is returned only upon completion of a sequence of memory references to both the odd and even banks. If the microengine 22f sorts the memory references into odd bank and even bank references and one of the banks, e.g., the even bank is drained of memory references before the odd bank but the signal is asserted on the last even reference, the memory controller 26a could conceivably signal back to a microengine that the memory request had completed, even though the odd bank reference had not been serviced. This occurrence could cause a coherency problem. The situation is avoided by providing the order queue 90c allowing a microengine to have multiple memory references outstanding of which only its last memory reference needs to signal a completion.

The SDRAM controller 26a also includes a high priority queue 90d. In the high priority queue 90d, an incoming memory reference from one of the microengines goes directly to the high priority queue and is operated upon at a higher priority than other memory references in the other queues. All of these queues, the even bank queue 90a, the odd bank queue 90b, the order queue 90c and the high priority queue, are implemented in a single RAM structure that is logically segmented into four different windows, each window having its own head and tail pointer. Since filling and draining operations are only a single input and a single output,

they can be placed into the same RAM structure to increase density of RAM structures.

The SDRAM controller 26a also includes core bus interface logic i.e., ASB bus 92. The ASB bus interface logic 92 interfaces the core processor 20 to the SDRAM controller 26a. The ASB bus is a bus that includes a 32 bit data path and a 28 bit address path. The data is accessed to and from memory through MEM ASB data device 98, e.g., a buffer. MEM ASB data device 98 is a queue for write data. If there is incoming data from the core processor 20 via ASB interface 92, the data can be stored into the MEM ASB device 98 and subsequently removed from MEM ASB device 98 through the SDRAM interface 110 to SDRAM memory 16a. Although not shown, the same queue structure can be provided for the reads. The SDRAM controller 26a also includes an engine 97 to pull data from the microengines and PCI bus.

Additional queues include the PCI address queue 94 and ASB read/write queue 96 that maintain a number of requests. The memory requests are sent to SDRAM interface 110 via multiplexer 106. The multiplexer 106 is controlled by the SDRAM arbiter 91 which detects the fullness of each of the queues and the status of the requests and from that decides priority based on a programmable value stored in a priority service control register 100.

Once control to the multiplexer 106 selects a memory reference request, the memory reference request, is sent to a decoder 108 where it is decoded and an address is generated. The decoded address is sent to the SDRAM interface 110 where it is decomposed into row and column

address strobes to access the SDRAM 16a and write or read data over data lines 16a sending data to bus 112. In one implementation, bus 112 is actually two separate buses instead of a single bus. The separate buses would include  
5 a read bus coupling the distributed microengines 22a-22f and a write bus coupling the distributed microengines 22a-22f.

A feature of the SDRAM controller 26a is that when a memory reference is stored in the queues 90, in addition to  
10 the optimized MEM bit that can be set, there is a "chaining bit". The chaining bit when set allows for special handling of contiguous memory references. As previously mentioned, the arbiter 12 controls which microengine will be selected to provide memory reference requests over the commander bus  
15 to queue 90 (FIG. 4). Assertion of the chain bit will control the arbiter to have the arbiter select the functional unit which previously requested that bus because setting of the chain bit indicates that the microengine issued a chain request.

20 Contiguous memory references will be received in queue 90 when the chaining bit is set. Those contiguous references will typically be stored in the order queue 90c because the contiguous memory references are multiple memory references from a single thread. In order to  
25 provide synchronization, the memory controller 26a need only signal at the end of the chained memory references when done. However, in an optimized memory chaining, (e.g, when optimized MEM bit and chaining bit are set) the memory references could go into different banks and  
30 potentially complete on one of the banks issuing the signal

"done" before the other bank was fully drained, thus destroying coherency. Therefore, the chain bit is used by the controller 110 to maintain the memory references from the current queue.

5 Referring to FIG. 4A, a flow representation of the arbitration policy in the SDRAM controller 26a is shown. The arbitration policy favors chained microengine memory requests. The process 115 starts by examining for Chained microengine memory reference requests 115a . The process  
10 115 stays at the chained requests until the chain bit is cleared. The process examines ASB bus requests 115b followed by PCI bus requests 115c, High Priority Queue Service 115d, Opposite Bank Requests 115e, Order Queue Requests 115f, and Same Bank Requests 115g. Chained  
15 request are serviced completely, whereas services 115b-115d are serviced in round robin order. Only when services 115a-115d are fully drained does the process handle services 115e-115g. Chained microengine memory reference requests are when the previous SDRAM memory request has the  
20 chain bit set. When the chain bit is set then the arbitration engine simply services the same queue again, until the chain bit is cleared. The ASB is higher priority than PCI due to the severe performance penalty imposed on the Strong arm core when the ASB is in wait state. PCI has  
25 higher priority than the microengines due to the latency requirements of PCI. However with other buses, the arbitration priority could be different.

As shown in FIG. 4B, typical timing of a memory without active memory optimization and with active memory  
30 optimization is shown. As can be seen, the use of active



memory optimizations maximizes the use of the bus and thus hides the inherent latency within physical SDRAM devices. In this example, a non-optimized access can take 14 cycles while optimized access can take 7 cycles.

5        Referring to FIG. 5, the memory controller 26b for the SRAM is shown. The memory controller 26b includes an address and command queue 120. While the memory controller 26a (FIG. 4) has a queue for memory optimization based on odd and even banking, memory controller 26b is optimized  
10        based on the type of memory operation, i.e., a read or a write. The address and command queue 120 includes a high priority queue 120a, a read queue 120b which is the predominant memory reference function that an SRAM performs, and an order queue 120c which in general will  
15        include all writes to SRAM and reads that are to be non-optimized. Although not shown, the address and command queue 120 could also include a write queue.

      The SRAM controller 26b also includes core bus interface logic i.e., ASB bus 122. The ASB bus interface  
20        logic 122 interfaces the core processor 20 to the SRAM controller 26b. The ASB bus is a bus that includes a 32 bit data path and a 28 bit address path. The data is accessed to and from memory through MEM ASB data device 128, e.g., a buffer. MEM ASB data device 128 is a queue  
25        for write data. If there is incoming data from the core processor 20 via ASB interface 122, the data can be stored into the MEM ASB device 128 and subsequently removed from MEM ASB device 128 through SRAM interface 140 to SRAM memory 16b. Although not shown, the same queue structure  
30        can be provided for reads. The SRAM controller 26b also

includes an engine 127 to pull data from the microengines and PCI bus.

The memory requests are sent to SRAM interface 140 via multiplexer 126. The multiplexer 126 is controlled by the  
5 SRAM arbiter 131 which detects the fullness of each of the queues and the status of the requests and from that decides priority based on a programmable value stored in a priority service control register 130. Once control to the multiplexer 126 selects a memory reference request, the  
10 memory reference request, is sent to a decoder 138 where it is decoded and an address is generated.

The SRAM Unit maintains control of the Memory Mapped off-chip SRAM and Expansion ROM. The SRAM controller 26b can address, e.g., 16 MBytes, with, e.g., 8 MBytes mapped  
15 for SRAM 16b, and 8 MBytes reserved for special functions including: Boot space via flashrom 16c; and Console port access for MAC devices 13a, 13b and access to associated (RMON) counters. The SRAM is used for local look-up tables and queue management functions.

20 The SRAM controller 26b supports the following transactions:

Microengine requests	(via private bus)	to/from SRAM.
Core Processor	(via ASB bus)	to/from SRAM.

25 The SRAM controller 26b performs memory reference sorting to minimize delays (bubbles) in the pipeline from the SRAM interface 140 to memory 16b. The SRAM controller 26b does memory reference sorting based on the read function. A bubble can either be 1 or 2 cycles depending  
30 on the type of memory device employed.

The SRAM controller 26b includes a lock lookup device 142 which is an eight (8) entry address content addressable memory for look-ups of read locks. Each position includes a valid bit that is examined by subsequent read-lock requests. The address and command queue 120 also includes a Read Lock Fail Queue 120d. The Read Lock Fail Queue 120d is used to hold read memory reference requests that fail because of a lock existing on a portion of memory. That is, one of the microengines issues a memory request that has a read lock request that is processed in address and control queue 120. The memory request will operate on either the order queue 120c or the read queue 120b and will recognize it as a read lock request. The controller 26b will access lock lookup device 142 to determine whether this memory location is already locked. If this memory location is locked from any prior read lock request, then this memory lock request will fail and will be stored in the read lock fail queue 120d. If it is unlocked or if 142 shows no lock on that address, then the address of that memory reference will be used by the SRAM interface 140 to perform a traditional SRAM address read/write request to memory 16b. The command controller and address generator 138 will also enter the lock into the lock look up device 142 so that subsequent read lock requests will find the memory location locked. A memory location is unlocked by operation of the a microcontrol instruction in a program after the need for the lock has ended. The location is unlocked by clearing the valid bit in the CAM. After an unlock, the read lock fail queue 120d becomes the highest priority queue giving all queued read lock misses, a chance

to issue a memory lock request.

As shown in FIG. 5A, typical timing of a static random access memory without active memory optimization and with active memory optimization is shown. As can be seen, 5 grouping reads and writes improves cycletime eliminating dead cycles.

Referring to FIG. 6, communication between the microengines 22 and the FBUS interface Logic (FBI) is shown. The FBUS interface 28 in a network application can 10 performs header processing of incoming packets from the FBUS 18. A key function which the FBUS interface performs is extraction of packet headers, and a microprogrammable source/destination/protocol hashed lookup in SRAM. If the hash does not successfully resolve, the packet header is 15 promoted to the core processor 28 for more sophisticated processing.

The FBI 28 contains a Transmit FIFO 182, a Receive FIFO 183, a HASH unit 188 and FBI control and status registers 189. These four units communicate with the 20 microengines 22, via a time-multiplexed access to the SRAM bus 38 which is connected to the transfer registers 78, 80 in the microengines. That is, all communications to and from the microengines are via the transfer registers 78, 80. The FBUS interface 28 includes a push state machine 25 200 for pushing data into the transfer registers during the time cycles which the SRAM is NOT using the SRAM data bus (part of bus 38) and a pull state machine 202 for fetching data from the transfer registers in the respective microengine.

30 The Hashing unit includes a pair of FIFO's 188a, 188b.

The hash unit determines that the FBI 28 received an FBI\_hash request. The hash unit 188 fetches hash keys from the calling microengine 22. After the keys are fetched and hashed, the indices are delivered back to the calling  
5 microengine 22. Up to three hashes are performed under a single FBI\_hash request. The busses 34 and 38 are each unidirectional: SDRAM\_push/pull\_data, and Sbus\_push/pull\_data. Each of these busses require control signals which will provide read/write controls to the  
10 appropriate microengine 22 Transfer registers.

Generally, transfer registers require protection from the context controlling them to guarantee read correctness. In particular, if a write transfer register is being used by a thread\_1 to provide data to the SDRAM 16a, thread\_1  
15 must not overwrite this register until the signal back from SDRAM controller 26a indicates that this register has been promoted and may now be re-used. Every write does not require a signal back from the destination indicating that the function has been completed, because if the thread  
20 writes to the same command queue at that destination with multiple requests, the order of the completion is guaranteed within that command queue, thus only the last command requires the signaling back to the thread. However, if the thread uses multiple command queues (order  
25 and read), then these command requests must be broken into separate context tasks, so that ordering is maintained via context swapping. The exception case indicated at the beginning of this paragraph is relative to a certain class of operations using an unsolicited PUSH to transfer  
30 registers from the FBI for FBUS status information. In

order to protect read/write determinism on the transfer registers, the FBI provides a special Push\_protect signal when these special FBI push operations are set up.

Any microengine 22 that uses the FBI unsolicited push  
5 technique must test the protection flag prior to accessing  
the FBUS interface/microengine agreed upon transfer  
registers. If the flag is not asserted, then the transfer  
registers may be accessed by the microengine. If the flag  
is Asserted then the context should wait N cycles prior to  
10 accessing the registers. A priori this count is determined  
by the number of transfer registers being pushed, plus a  
frontend protection window. The basic idea is that the  
microengine must test this flag then quickly move the data  
which it wishes to read from the read transfer registers to  
15 GPR's in contiguous cycles, so the push engine does not  
collide with the microengine read.

Other Embodiments

It is to be understood that while the invention has been described in conjunction with the detailed description ,  
5 thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

10

What is claimed is:

## CLAIMS

1. A parallel hardware-based multithreaded processor comprises:
  - 5 a general purpose processor that coordinates system functions; and
  - a plurality of microengines that support multiple hardware threads.
- 10 2. The processor of claim 1 wherein the general purpose processor load microcontrol programs in the plurality of microcontrol engines.
3. The processor of claim 1 further comprising a memory  
15 control system.
4. The processor of claim 1 wherein the memory control system comprises a synchronous dynamic random access memory controller that sorts memory references based on whether  
20 the memory references are directed to an even bank or an odd bank of memory.
5. The processor of claim 1 wherein the memory control system comprises a static random access memory controller  
25 that optimizes memory references based upon whether the memory references are read references or write references.



6. The processor of claim 1 wherein each of the plurality of microengines employ hardware-based context swapping amongst a plurality of threads that are independently executable within each of the microengines.

5

7. The processor of claim 1 further comprising a high speed bus interface that couples the processor to a communication bus.

10 8. The processor of claim 1 further comprising a bus interface that couples the processor to a computer system bus.

9. The processor of claim 1 further comprising an  
15 internal bus arrangement to couple shared resources in the processor to the plurality of microengines.

10. The processor of claim 9 wherein the internal bus arrangement to couple shared resources, comprises:

20 a first bus to couple the general purpose processor to the plurality of microengines.

11. The processor of claim 9 wherein the internal bus arrangement to couple shared resources, comprises:

25 a translator device that translates requests from the general purpose processor to the microengines; and  
a first bus to couple the general purpose processor to the plurality of microengines.

12. The processor of claim 3 wherein the internal bus arrangement to couple shared resources, comprises:

a translator device that translates requests from the general purpose processor to the microengines; and

5 a first bus to couple the general purpose processor to the plurality of microengines; and

a second bus to couple the general purpose processor to the memory control system.

10 13. The processor of claim 11, further comprising a third bus to couple the microengines to external bus interfaces.

14. The processor of claim 8 wherein the shared resources comprise:

15 a memory controller for controlling access to low latency memory;

a memory controller for controlling an access to high bandwidth memory;

20 a bus interface for controlling access to a communications bus; and

a bus interface for controlling access to a computer bus.

15. The processor of claim 1 wherein each one of the  
25 microengines includes a program counter to uniquely identify a position of a thread during execution in the microengine.

16. The processor of claim 1 wherein the processor  
30 supports global signaling to each of the microengines.

17. The processor of claim 16 wherein the global signaling is available to each thread in each microengine.

5 18. The processor of claim 17 wherein the global signaling is available to each thread to permit each thread to take a branch.

19. A parallel hardware-based multithreaded processor  
10 comprises:

a general purpose processor that coordinates system functions;

a plurality of microengines that support multiple hardware threads;

15 a memory control system comprising:

a first memory controller that sorts memory references based on whether the memory references are directed to an even bank or an odd bank of memory; and

a second memory controller that optimizes memory  
20 references based upon whether the memory references are read references or write references.

20. The parallel hardware-based multithreaded processor of claim 19 wherein the first memory controller controls  
25 synchronous dynamic random access memory and the second memory controller controls static random access static memory.

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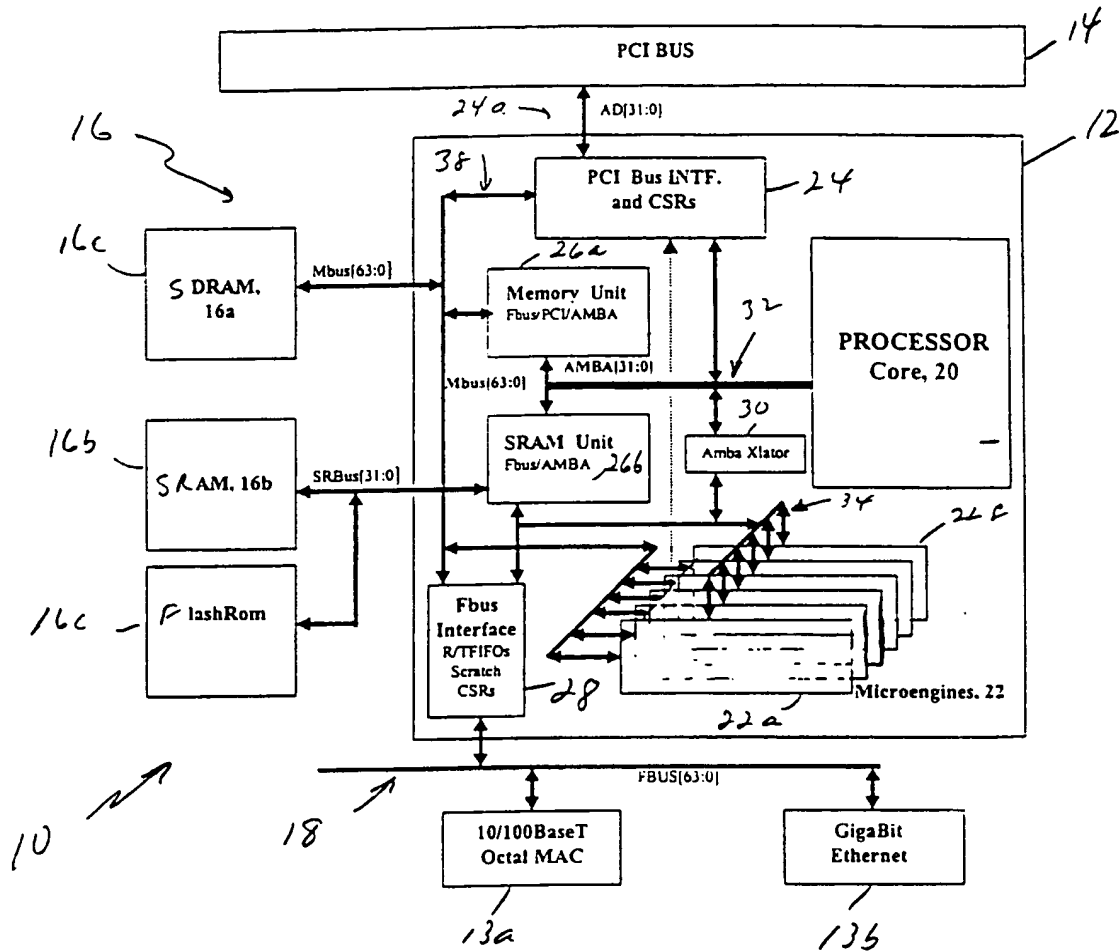


FIG. 1



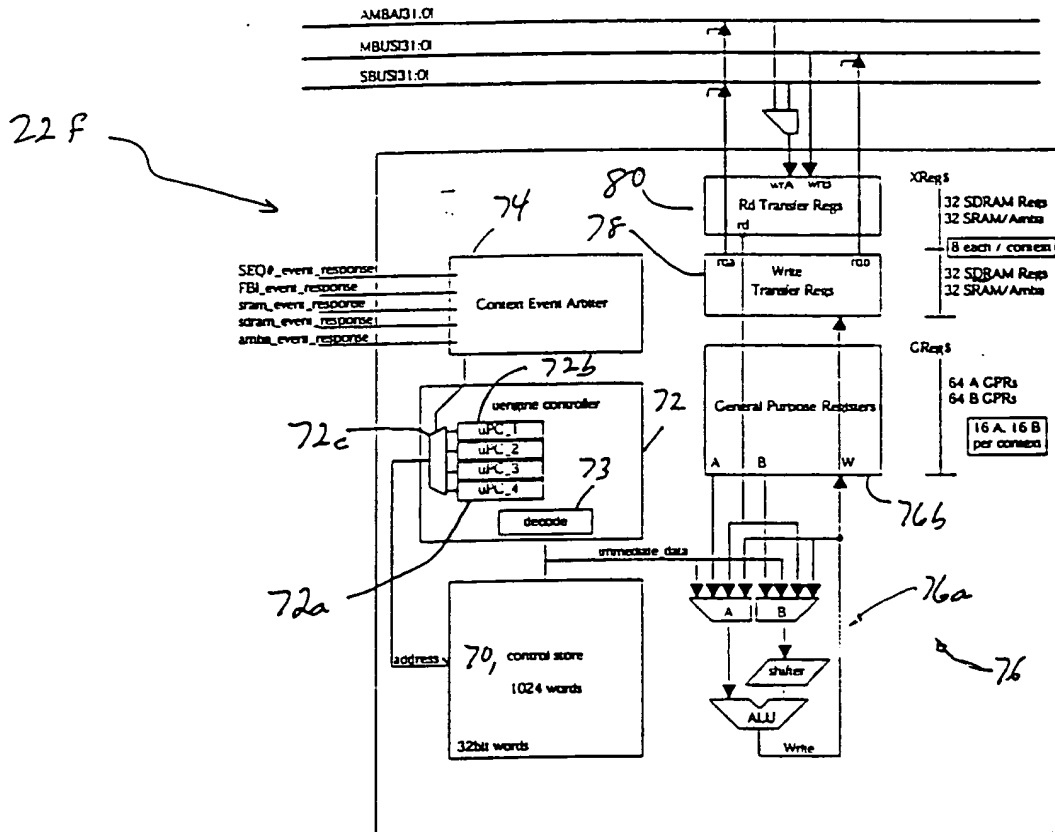


FIG. 3

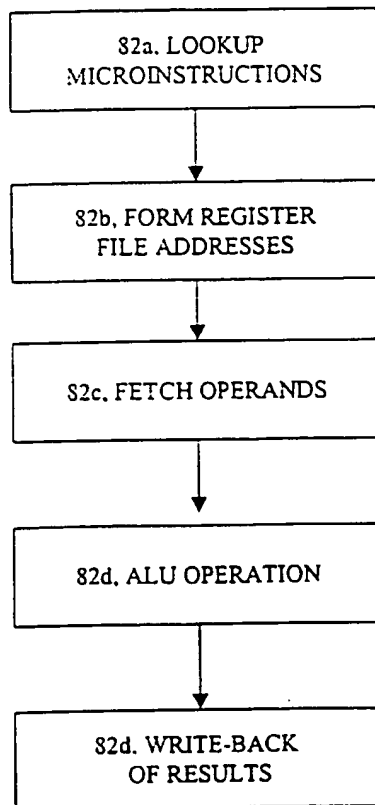


FIG. 3A

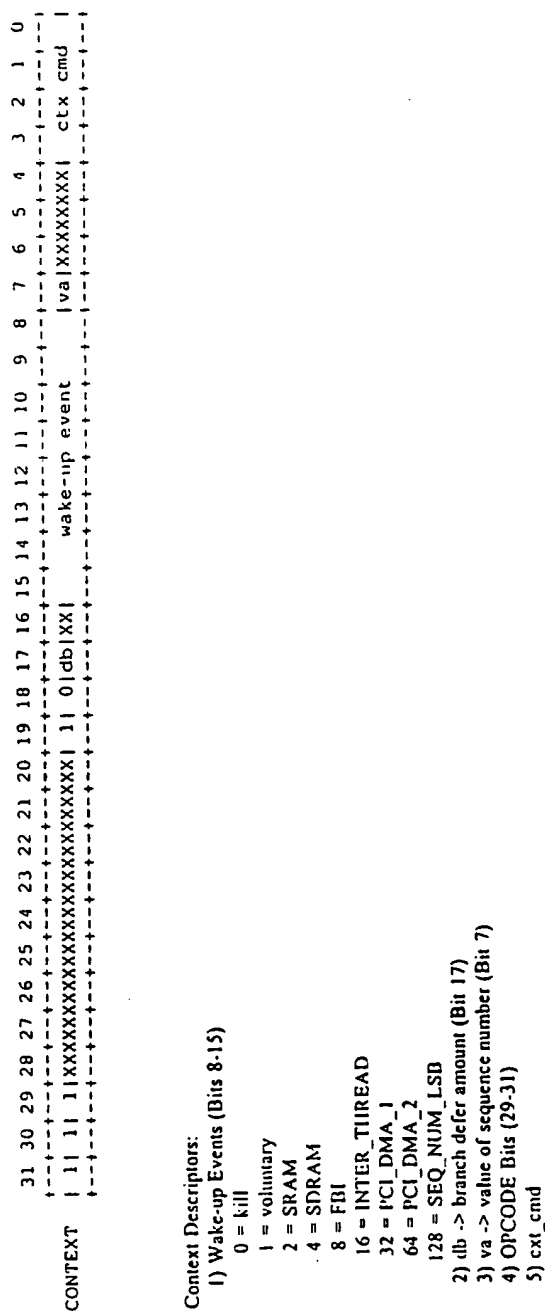


FIG. 3B



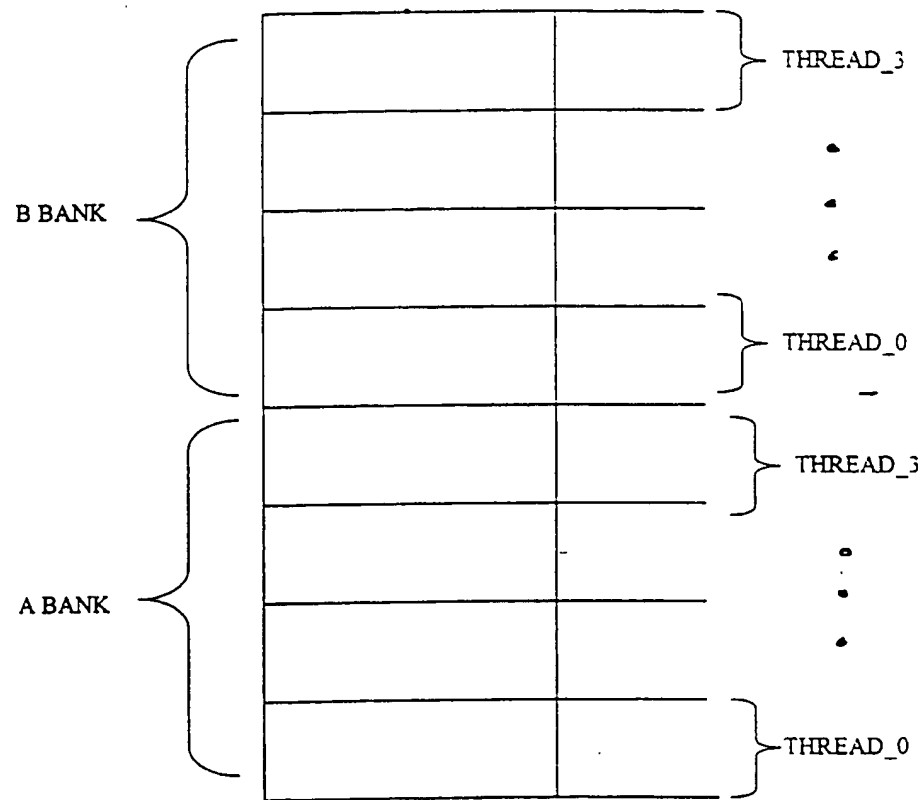
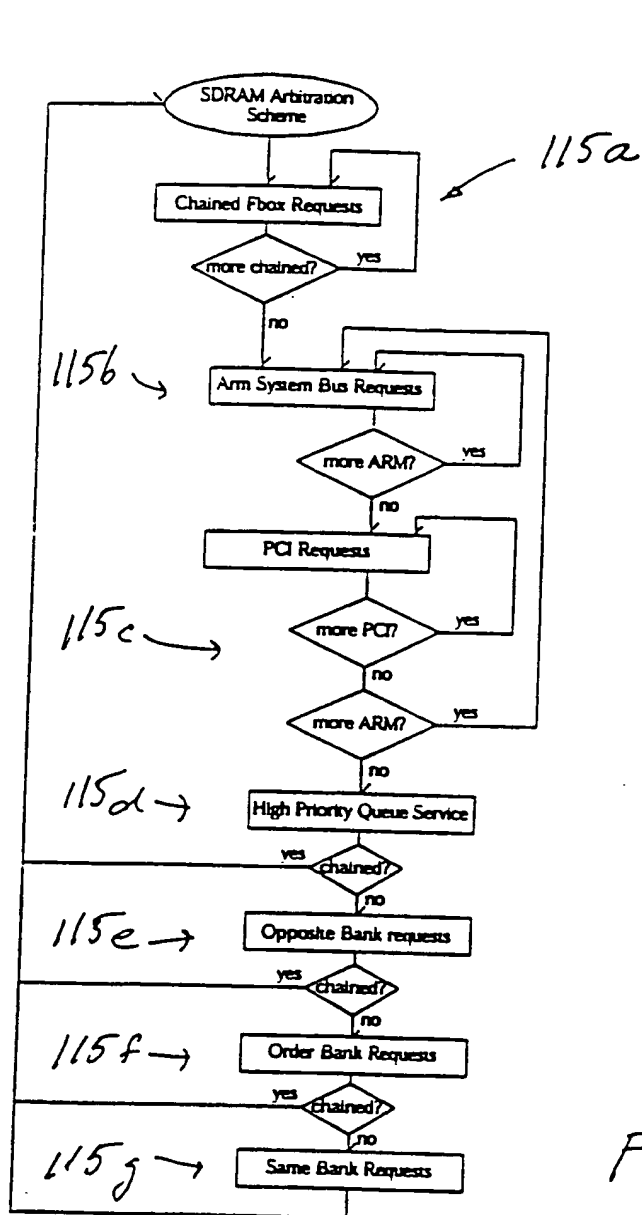


FIG. 3C

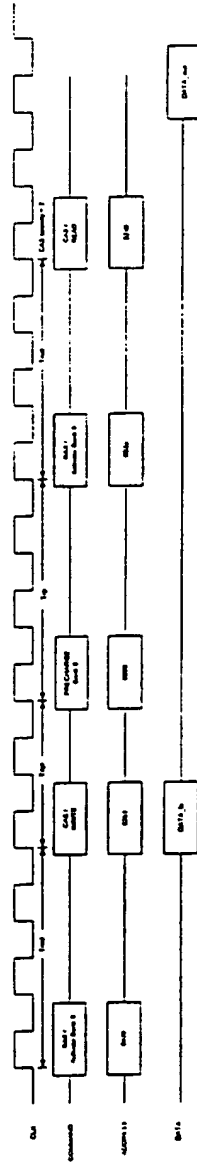




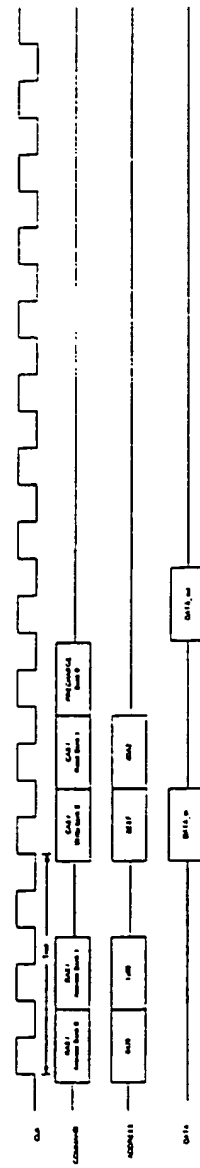
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SINGLE QUADWORD WRITE FOLLOWED BY A SINGLE QUADWORD READ

without Active Memory Optimization



with Active Memory Optimization



where  $T_{rcd}$  = RAS to CAS delay  
 $T_{dpl}$  = DATA Input to Precharge Delay  
 $T_{rp}$  = Time to Precharge

FIG. 4B

10/12

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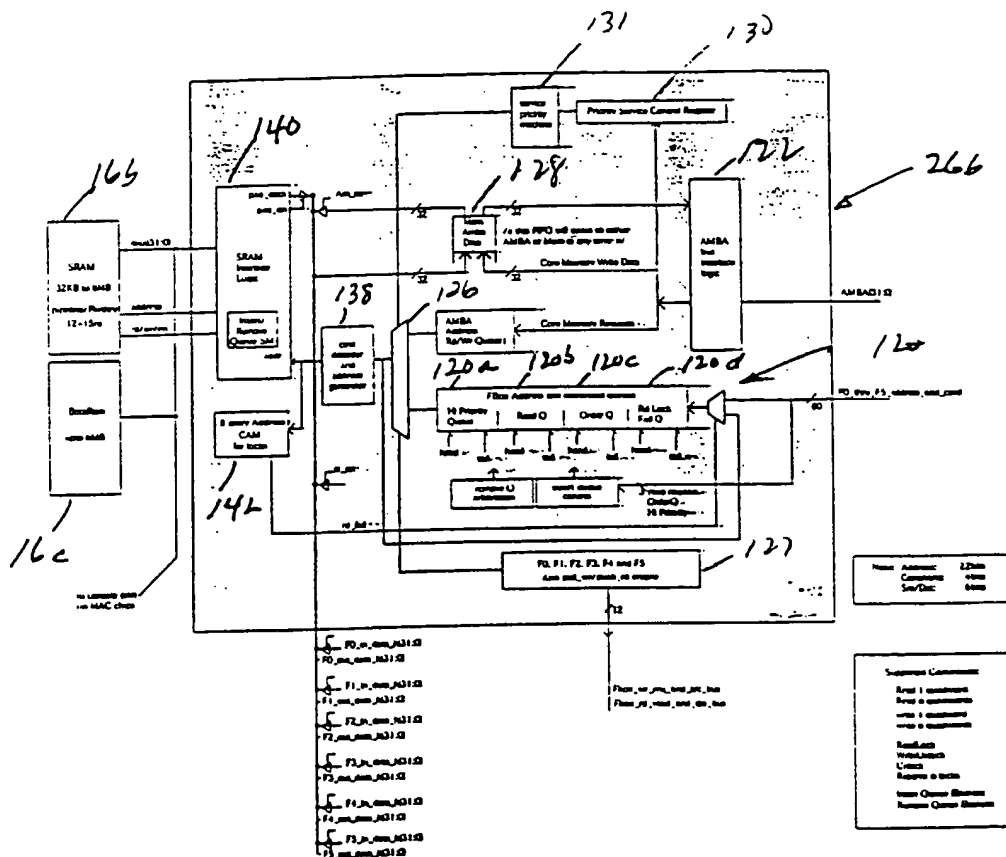
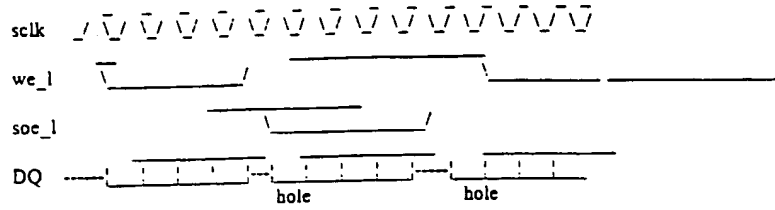


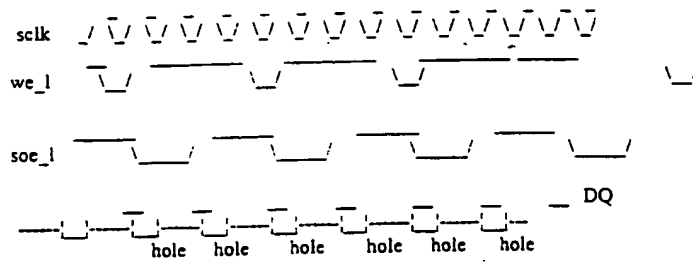
FIG. 5

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4 Writes and 4 Reads followed by more reads with optimization



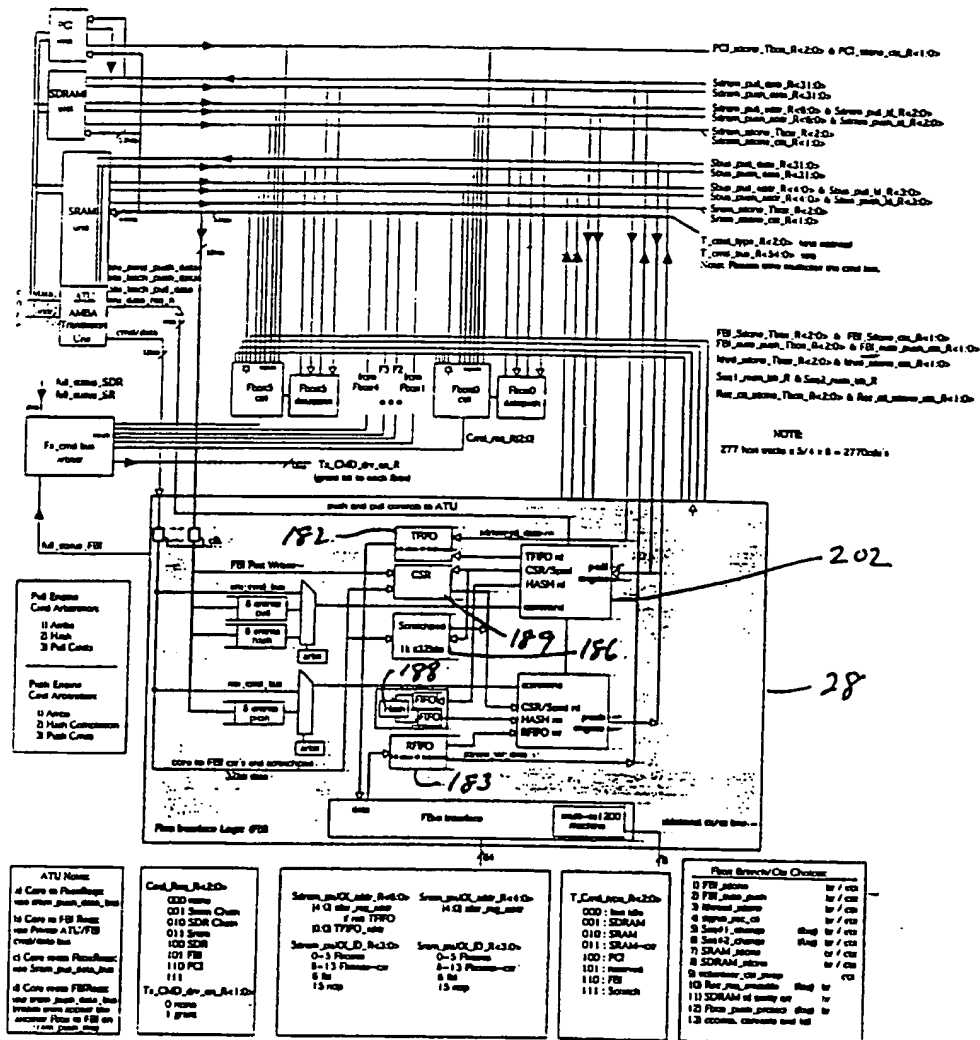
4 Writes and 4 Reads without optimization



10 cycles vs. 14.

FIG. 5A

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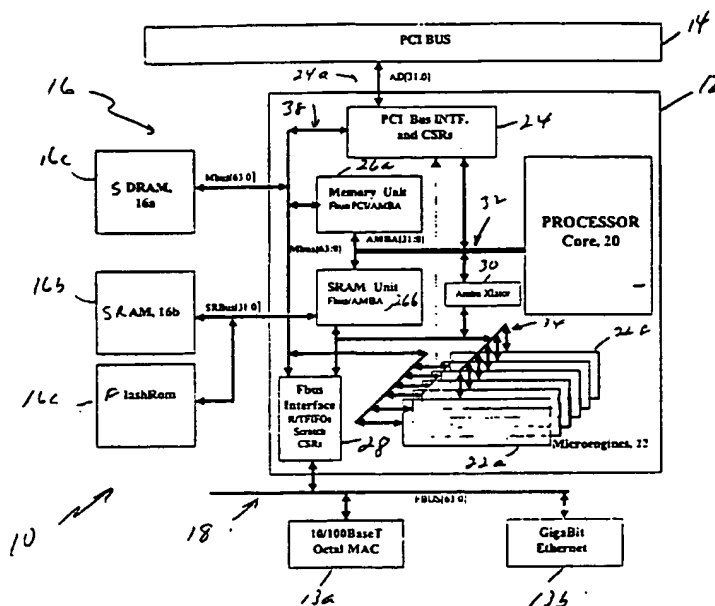
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[Continued on next page]

(54) Title: PARALLEL PROCESSOR ARCHITECTURE



(57) Abstract: A parallel hardware-based multithreaded processor is described. The processor includes a general purpose processor that coordinates system functions and a plurality of microengines that support multiple hardware threads. The processor also includes a memory control system that has a first memory controller that sorts memory references based on whether the memory references are directed to an even bank or an odd bank of memory and a second memory controller that optimizes memory references based upon whether the memory references are read references or write reference.





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# INTERNATIONAL SEARCH REPORT

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PCT/US 00/22322

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 G06F15/78 G06F15/80 G06F9/38

According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

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☒ Further documents are listed in the continuation of box C.

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Int: ional Application No  
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

Int .ional Application No

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## SDRAM CONTROLLER FOR PARALLEL PROCESSOR ARCHITECTURE

5

## BACKGROUND

This invention relates to memory controllers particularly for use in parallel processing systems.

Parallel processing is an efficient form of information processing of concurrent events in a computing process. Parallel processing demands concurrent execution of many programs in a computer, in contrast to sequential processing. In the context of a parallel processor, parallelism involves doing more than one thing at the same time. Unlike a serial paradigm where all tasks are performed sequentially at a single station or a pipelined machine where tasks are performed at specialized stations, with parallel processing, a plurality of stations are provided with each capable of performing all tasks. That is, in general all or a plurality of the stations work simultaneously and independently on the same or common elements of a problem. Certain problems are suitable for solution by applying parallel processing.

Memory systems used in parallel processing tasks can be inefficient.

25

## SUMMARY

According to an aspect of the present invention, a memory controller for a random access memory includes an address and command queue that holds memory references from a plurality of microcontrol functional units. The memory controller also includes a first read/write queue that

holds memory reference from a computer bus and a second read/write queue that holds memory references from a core processor. The memory controller also includes control logic including an arbiter that detects the fullness of  
5 each of the queues and a status of outstanding memory reference to select a memory reference from one of the queues.

According to an additional aspect of the invention, the controller has control logic that is  
10 responsive to a chaining bit that when set allows for special handling of contiguous memory references. The chaining bit controls the arbiter to have the arbiter select the functional unit which previously requested a bus. Assertion of the chaining bit will control the  
15 arbiter when the optimized memory bit is also set to maintain the memory references from a current queue.

One or more of the following advantages may be provided by one or more aspects of the invention.

The controller uses memory reference sorting when  
20 an optimized memory bit is set. The memory reference sorting is based on bank accesses that allows hiding of pre-charges from one bank to another bank. Specifically, if a memory system is organized into an odd bank and an even bank, while the memory controller is operating on the  
25 odd bank, the memory controller can start precharging the even bank. Precharging is possible if memory references alternate between odd and even banks.

Additionally, other optimizations can be used. For example, merging optimizations where operations that  
30 can be merged, are merged prior to memory access, open page



optimizations where by examining addresses an opened page of memory is not reopened, chaining, and refreshing mechanisms, can be employed.

Another feature of the controller is that when a  
5 memory reference is stored in the queues, in addition to the optimized memory bit that can be set, the controller also uses a Achaining bit@. The chaining bit when set allows for special handling of contiguous memory references. Assertion of the chaining bit will control the  
10 arbiter to have the arbiter select the functional unit which previously requested a memory bus.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a communication  
15 system employing a hardware-based multithreaded processor.

FIG. 2 is a detailed block diagram of the hardware-based multithreaded processor of FIG. 1.

FIG. 3 is a block diagram of a microengine functional unit employed in the hardware-based  
20 multithreaded processor of FIGS. 1 and 2.

FIG. 3A is a block diagram of a pipeline in the microengine of FIG. 3.

FIG. 3B. is diagram that shows a format for a context switch instruction.

25 FIG. 3C is a block diagram showing general purpose register address arrangement.

FIG. 4 is a block diagram of a memory controller for enhanced bandwidth operation used in the hardware-based multithreaded processor.

30

FIG. 4A is a flow chart that represents an arbitration policy in an SDRAM controller of FIG. 4.

FIG. 4B is a timing diagram that shows advantages of optimizing SDRAM controller.

5           FIG. 5 is a block diagram of a memory controller for latency limited operations used in the hardware-based multithreaded processor.

FIG. 5A is a timing diagram that shows advantages of optimizing SRAM controller.

10           FIG. 6 is a block diagram of a communication bus interface in the processor of FIG. 1.

#### DESCRIPTION

15   Architecture:

Referring to FIG. 1, a communication system 10 includes a parallel, hardware-based multithreaded processor 12. The hardware-based multithreaded processor 12 is coupled to a bus such as a PCI bus 14, a memory system 16 and a second bus 18. The system 10 is especially useful for tasks that can be broken into parallel subtasks or functions. Specifically hardware-based multithreaded processor 12 is useful for tasks that are bandwidth oriented rather than latency oriented. The hardware-based multithreaded processor 12 has multiple microengines 22 each with multiple hardware controlled threads that can be simultaneously active and independently work on a task.

The hardware-based multithreaded processor 12 also includes a central controller 20 that assists in loading microcode control for other resources of the hardware-based multithreaded processor 12 and performs

other general purpose computer type functions such as handling protocols, exceptions, extra support for packet processing where the microengines pass the packets off for more detailed processing such as in boundary conditions.

- 5 In one embodiment, the processor 20 is a Strong Arm<sup>7</sup> (Arm is a trademark of ARM Limited, United Kingdom) based architecture. The general purpose microprocessor 20 has an operating system. Through the operating system the processor 20 can call functions to operate on microengines  
10 22a-22f. The processor 20 can use any supported operating system preferably a real time operating system. For the core processor implemented as a Strong Arm architecture, operating systems such as, MicrosoftNT real-time, VXWorks and  $\mu$ CUS, a freeware operating system available over the  
15 Internet, can be used.

- The hardware-based multithreaded processor 12 also includes a plurality of function microengines 22a-22f. Functional microengines (microengines) 22a-22f each maintain a plurality of program counters in hardware and  
20 states associated with the program counters. Effectively, a corresponding plurality of sets of threads can be simultaneously active on each of the microengines 22a-22f while only one is actually operating at any one time.

- In one embodiment, there are six microengines  
25 22a-22f as shown. Each microengines 22a-22f has capabilities for processing four hardware threads. The six microengines 22a-22f operate with shared resources including memory system 16 and bus interfaces 24 and 28. The memory system 16 includes a Synchronous Dynamic Random  
30 Access Memory (SDRAM) controller 26a and a Static Random

Access Memory (SRAM) controller 26b. SDRAM memory 16a and SDRAM controller 26a are typically used for processing large volumes of data, e.g., processing of network payloads from network packets. The SRAM controller 26b and SRAM  
5 memory 16b are used in a networking implementation for low latency, fast access tasks, e.g., accessing look-up tables, memory for the core processor 20, and so forth.

The six microengines 22a-22f access either the SDRAM 16a or SRAM 16b based on characteristics of the data.  
10 Thus, low latency, low bandwidth data is stored in and fetched from SRAM, whereas higher bandwidth data for which latency is not as important, is stored in and fetched from SDRAM. The microengines 22a-22f can execute memory reference instructions to either the SDRAM controller 26a  
15 or SRAM controller 16b.

Advantages of hardware multithreading can be explained by SRAM or SDRAM memory accesses. As an example, an SRAM access requested by a Thread\_0, from a microengine will cause the SRAM controller 26b to initiate an access to  
20 the SRAM memory 16b. The SRAM controller controls arbitration for the SRAM bus, accesses the SRAM 16b, fetches the data from the SRAM 16b, and returns data to a requesting microengine 22a-22b. During an SRAM access, if the microengine e.g., 22a had only a single thread that  
25 could operate, that microengine would be dormant until data was returned from the SRAM. By employing hardware context swapping within each of the microengines 22a-22f, the hardware context swapping enables other contexts with unique program counters to execute in that same  
30 microengine. Thus, another thread e.g., Thread\_1 can

function while the first thread, e.g., Thread\_0, is awaiting the read data to return. During execution, Thread\_1 may access the SDRAM memory 16a. While Thread\_1 operates on the SDRAM unit, and Thread\_0 is operating on the SRAM unit, a new thread, e.g., Thread\_2 can now operate in the microengine 22a. Thread\_2 can operate for a certain amount of time until it needs to access memory or perform some other long latency operation, such as making an access to a bus interface. Therefore, simultaneously, the processor 12 can have a bus operation, SRAM operation and SDRAM operation all being completed or operated upon by one microengine 22a and have one more thread available to process more work in the data path.

The hardware context swapping also synchronizes completion of tasks. For example, two threads could hit the same shared resource e.g., SRAM. Each one of these separate functional units, e.g., the FBUS interface 28, the SRAM controller 26a, and the SDRAM controller 26b, when they complete a requested task from one of the microengine thread contexts reports back a flag signaling completion of an operation. When the flag is received by the microengine, the microengine can determine which thread to turn on.

One example of an application for the hardware-based multithreaded processor 12 is as a network processor. As a network processor, the hardware-based multithreaded processor 12 interfaces to network devices such as a media access controller device e.g., a 10/100BaseT Octal MAC 13a or a Gigabit Ethernet device 13b. In general, as a network processor, the hardware-based multithreaded processor 12

can interface to any type of communication device or interface that receives/sends large amounts of data. Communication system 10 functioning in a networking application could receive a plurality of network packets from the devices 13a, 13b and process those packets in a parallel manner. With the hardware-based multithreaded processor 12, each network packet can be independently processed.

Another example for use of processor 12 is a print engine for a postscript processor or as a processor for a storage subsystem, i.e., RAID disk storage. A further use is as a matching engine. In the securities industry for example, the advent of electronic trading requires the use of electronic matching engines to match orders between buyers and sellers. These and other parallel types of tasks can be accomplished on the system 10.

The processor 12 includes a bus interface 28 that couples the processor to the second bus 18. Bus interface 28 in one embodiment couples the processor 12 to the so-called FBUS 18 (FIFO bus). The FBUS interface 28 is responsible for controlling and interfacing the processor 12 to the FBUS 18. The FBUS 18 is a 64-bit wide FIFO bus, used to interface to Media Access Controller (MAC) devices.

The processor 12 includes a second interface e.g., a PCI bus interface 24 that couples other system components that reside on the PCI 14 bus to the processor 12. The PCI bus interface 24, provides a high speed data path 24a to memory 16 e.g., the SDRAM memory 16a. Through that path data can be moved quickly from the SDRAM 16a

through the PCI bus 14, via direct memory access (DMA) transfers. The hardware based multithreaded processor 12 supports image transfers. The hardware based multithreaded processor 12 can employ a plurality of DMA channels so if  
5 one target of a DMA transfer is busy, another one of the DMA channels can take over the PCI bus to deliver information to another target to maintain high processor 12 efficiency. Additionally, the PCI bus interface 24 supports target and master operations. Target operations  
10 are operations where slave devices on bus 14 access SDRAMs through reads and writes that are serviced as a slave to target operation. In master operations, the processor core 20 sends data directly to or receives data directly from the PCI interface 24.

15 Each of the functional units are coupled to one or more internal buses. As described below, the internal buses are dual, 32 bit buses (i.e., one bus for read and one for write). The hardware-based multithreaded processor 12 also is constructed such that the sum of the bandwidths  
20 of the internal buses in the processor 12 exceed the bandwidth of external buses coupled to the processor 12. The processor 12 includes an internal core processor bus 32, e.g., an ASB bus (Advanced System Bus) that couples the processor core 20 to the memory controller 26a, 26c and to  
25 an ASB translator 30 described below. The ASB bus is a subset of the so called AMBA bus that is used with the Strong Arm processor core. The processor 12 also includes a private bus 34 that couples the microengine units to SRAM controller 26b, ASB translator 30 and FBUS interface 28. A  
30 memory bus 38 couples the memory controller 26a, 26b to the

bus interfaces 24 and 28 and memory system 16 including flashrom 16c used for boot operations and so forth.

Referring to FIG. 2, each of the microengines 22a-22f includes an arbiter that examines flags to  
5 determine the available threads to be operated upon. Any thread from any of the microengines 22a-22f can access the SDRAM controller 26a, SDRAM controller 26b or FBUS interface 28. The memory controllers 26a and 26b each include a plurality of queues to store outstanding memory  
10 reference requests. The queues either maintain order of memory references or arrange memory references to optimize memory bandwidth. For example, if a thread\_0 has no dependencies or relationship to a thread\_1, there is no reason that thread 1 and 0 cannot complete their memory  
15 references to the SRAM unit out of order. The microengines 22a-22f issue memory reference requests to the memory controllers 26a and 26b. The microengines 22a-22f flood the memory subsystems 26a and 26b with enough memory reference operations such that the memory subsystems 26a  
20 and 26b become the bottleneck for processor 12 operation.

If the memory subsystem 16 is flooded with memory requests that are independent in nature, the processor 12 can perform memory reference sorting. Memory reference  
25 reference sorting, as described below, reduces dead time or a bubble that occurs with accesses to SRAM. With memory references to SRAM, switching current direction on signal lines between reads and writes produces a bubble or a dead time waiting for current to settle on conductors coupling  
30 the SRAM 16b to the SRAM controller 26b.

FIG. 2 FOR SRAM 16b



That is, the drivers that drive current on the bus need to settle out prior to changing states. Thus, repetitive cycles of a read followed by a write can degrade peak bandwidth. Memory reference sorting allows the processor 12 to organize references to memory such that long strings of reads can be followed by long strings of writes. This can be used to minimize dead time in the pipeline to effectively achieve closer to maximum available bandwidth. Reference sorting helps maintain parallel hardware context threads. On the SDRAM, reference sorting allows hiding of pre-charges from one bank to another bank. Specifically, if the memory system 16b is organized into an odd bank and an even bank, while the processor is operating on the odd bank, the memory controller can start precharging the even bank. Precharging is possible if memory references alternate between odd and even banks. By ordering memory references to alternate accesses to opposite banks, the processor 12 improves SDRAM bandwidth. Additionally, other optimizations can be used. For example, merging optimizations where operations that can be merged, are merged prior to memory access, open page optimizations where by examining addresses an opened page of memory is not reopened, chaining, as will be described below, and refreshing mechanisms, can be employed.

The FBUS interface 28 supports Transmit and Receive flags for each port that a MAC device supports, along with an Interrupt flag indicating when service is warranted. The FBUS interface 28 also includes a controller 28a that performs header processing of incoming packets from the FBUS 18. The controller 28a extracts the

packet headers and performs a microprogrammable source/destination/protocol hashed lookup (used for address smoothing) in SRAM. If the hash does not successfully resolve, the packet header is sent to the processor core 20 for additional processing. The FBUS interface 28 supports the following internal data transactions:

	FBUS unit	(Shared bus SRAM)	to/from microengine.
	FBUS unit	(via private bus)	writes from SDRAM Unit.
10	FBUS unit	(via Mbus)	Reads to SDRAM.

The FBUS 18 is a standard industry bus and includes a data bus, e.g., 64 bits wide and sideband control for address and read/write control. The FBUS interface 28 provides the ability to input large amounts of data using a series of input and output FIFO=s 29a-29b. From the FIFOs 29a-29b, the microengines 22a-22f fetch data from or command the SDRAM controller 26a to move data from a receive FIFO in which data has come from a device on bus 18, into the FBUS interface 28. The data can be sent through memory controller 26a to SDRAM memory 16a, via a direct memory access. Similarly, the microengines can move data from the SDRAM 26a to interface 28, out to FBUS 18, via the FBUS interface 28.

Data functions are distributed amongst the microengines. Connectivity to the SRAM 26a, SDRAM 26b and FBUS 28 is via command requests. A command request can be a memory request or a FBUS request. For example, a command request can move data from a register located in a microengine 22a to a shared resource, e.g., an SDRAM

location, SRAM location, flash memory or some MAC address. The commands are sent out to each of the functional units and the shared resources. However, the shared resources do not need to maintain local buffering of the data. Rather, 5 the shared resources access distributed data located inside of the microengines. This enables microengines 22a-22f, to have local access to data rather than arbitrating for access on a bus and risk contention for the bus. With this feature, there is a 0 cycle stall for waiting for data 10 internal to the microengines 22a-22f.

The data buses, e.g., ASB bus 30, SRAM bus 34 and SDRAM bus 38 coupling these shared resources, e.g., memory controllers 26a and 26b are of sufficient bandwidth such that there are no internal bottlenecks. Thus, in order to 15 avoid bottlenecks, the processor 12 has an bandwidth requirement where each of the functional units is provided with at least twice the maximum bandwidth of the internal buses. As an example, the SDRAM can run a 64 bit wide bus at 83 MHz. The SRAM data bus could have separate read and 20 write buses, e.g., could be a read bus of 32 bits wide running at 166 MHz and a write bus of 32 bits wide at 166 MHz. That is, in essence, 64 bits running at 166 MHz which is effectively twice the bandwidth of the SDRAM.

The core processor 20 also can access the shared 25 resources. The core processor 20 has a direct communication to the SDRAM controller 26a to the bus interface 24 and to SRAM controller 26b via bus 32. However, to access the microengines 22a-22f and transfer registers located at any of the microengines 22a-22f, the 30 core processor 20 access the microengines 22a-22f via the

ASB Translator 30 over bus 34. The ASB translator 30 can physically reside in the FBUS interface 28, but logically is distinct. The ASB Translator 30 performs an address translation between FBUS microengine transfer register  
5 locations and core processor addresses (i.e., ASB bus) so that the core processor 20 can access registers belonging to the microengines 22a-22c.

Although microengines 22 can use the register set to exchange data as described below, a scratchpad memory 27  
10 is also provided to permit microengines to write data out to the memory for other microengines to read. The scratchpad 27 is coupled to bus 34.

The processor core 20 includes a RISC core 50 implemented in a five stage pipeline performing a single  
15 cycle shift of one operand or two operands in a single cycle, provides multiplication support and 32 bit barrel shift support. This RISC core 50 is a standard Strong Arm<sup>7</sup> architecture but it is implemented with a five stage pipeline for performance reasons. The processor core 20  
20 also includes a 16 kilobyte instruction cache 52, an 8 kilobyte data cache 54 and a prefetch stream buffer 56. The core processor 20 performs arithmetic operations in parallel with memory writes and instruction fetches. The core processor 20 interfaces with other functional units  
25 via the ARM defined ASB bus. The ASB bus is a 32-bit bi-directional bus 32.

Microengines:

Referring to FIG. 3, an exemplary one of the microengines 22a-22f, e.g., microengine 22f is shown. The microengine includes a control store 70 which, in one  
5 implementation, includes a RAM of here 1,024 words of 32 bit. The RAM stores a microprogram. The microprogram is loadable by the core processor 20. The microengine 22f also includes controller logic 72. The controller logic includes an instruction decoder 73 and program counter (PC)  
10 units 72a-72d. The four micro program counters 72a-72d are maintained in hardware. The microengine 22f also includes context event switching logic 74. Context event logic 74 receives messages (e.g., SEQ\_#\_EVENT\_RESPONSE; FBI\_EVENT\_RESPONSE; SRAM\_EVENT\_RESPONSE; SDRAM  
15 \_EVENT\_RESPONSE; and ASB\_EVENT\_RESPONSE) from each one of the shared resources, e.g., SRAM 26a, SDRAM 26b, or processor core 20, control and status registers, and so forth. These messages provide information on whether a requested function has completed. Based on whether or not  
20 a function requested by a thread has completed and signaled completion, the thread needs to wait for that completion signal, and if the thread is enabled to operate, then the thread is placed on an available thread list (not shown). The microengine 22f can have a maximum of e.g., 4 threads  
25 available.

In addition to event signals that are local to an executing thread, the microengines 22 employ signaling states that are global. With signaling states, an executing thread can broadcast a signal state to all

microengines 22. Receive Request Available signal, Any and all threads in the microengines can branch on these signaling states. These signaling states can be used to determine availability of a resource or whether a resource  
5 is due for servicing.

The context event logic 74 has arbitration for the four (4) threads. In one embodiment, the arbitration is a round robin mechanism. Other techniques could be used including priority queuing or weighted fair queuing. The  
10 microengine 22f also includes an execution box (EBOX) data path 76 that includes an arithmetic logic unit 76a and general purpose register set 76b. The arithmetic logic unit 76a performs arithmetic and logical functions as well as shift functions. The registers set 76b has a relatively  
15 large number of general purpose registers. As will be described in FIG. 3B, in this implementation there are 64 general purpose registers in a first bank, Bank A and 64 in a second bank, Bank B. The general purpose registers are windowed as will be described so that they are relatively  
20 and absolutely addressable.

The microengine 22f also includes a write transfer register stack 78 and a read transfer stack 80. These registers are also windowed so that they are relatively and absolutely addressable. Write transfer  
25 register stack 78 is where write data to a resource is located. Similarly, read register stack 80 is for return data from a shared resource. Subsequent to or concurrent with data arrival, an event signal from the respective shared resource e.g., the SRAM controller 26a, SDRAM  
30 controller 26b or core processor 20 will be provided to

context event arbiter 74 which will then alert the thread that the data is available or has been sent. Both transfer register banks 78 and 80 are connected to the execution box (EBOX) 76 through a data path. In one implementation, the  
5 read transfer register has 64 registers and the write transfer register has 64 registers.

As shown in FIG. 3A, the microengine datapath maintains a 5-stage micro-pipeline 82. This pipeline includes lookup of microinstruction words 82a, formation of  
10 the register file addresses 82b, read of operands from register file 82c, ALU, shift or compare operations 82d, and write-back of results to registers 82e. By providing a write-back data bypass into the ALU/shifter units, and by assuming the registers are implemented as a register file  
15 (rather than a RAM), the microengine can perform a simultaneous register file read and write, which completely hides the write operation.

The SDRAM interface 26a provides a signal back to the requesting microengine on reads that indicates whether  
20 a parity error occurred on the read request. The microengine microcode is responsible for checking the SDRAM read Parity flag when the microengine uses any return data. Upon checking the flag, if it was set, the act of branching on it clears it. The Parity flag is only sent when the  
25 SDRAM is enabled for checking, and the SDRAM is parity protected. The microengines and the PCI Unit are the only requestors notified of parity errors. Therefore, if the processor core 20 or FIFO requires parity protection, a microengine assists in the request. The microengines 22a-  
30 22f support conditional branches. The worst case

conditional branch latency (not including jumps) occurs when the branch decision is a result of condition codes being set by the previous microcontrol instruction. The latency is shown below in Table 1:

5

```

                                | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
                                +---+---+---+---+---+---+---+
microstore lookup      | n1 | cb | n2 | XX | b1 | b2 | b3 | b4 |
reg addr gen           |    | n1 | cb | XX | XX | b1 | b2 | b3 |
10 reg file lookup     |    |    | n1 | cb | XX | XX | b1 | b2 |
ALU/shifter/cc         |    |    |    | n1 | cb | XX | XX | b1 |
write back             |    |    | m2 |    | n1 | cb | XX | XX |

```

where nx is pre-branch microword (n1 sets cc's)

cb is conditional branch

bx is post-branch microword

XX is aborted microword

As shown in Table 1, it is not until cycle 4 that the condition codes of n1 are set, and the branch decision can be made (which in this case causes the branch path to be looked up in cycle 5). The microengine incurs a 2-cycle branch latency penalty because it must abort operations n2 and n3 (the 2 microwords directly after the branch) in the pipe, before the branch path begins to fill the pipe with operation b1. If the branch is not taken, no microwords are aborted and execution continues normally. The microengines have several mechanisms to reduce or eliminate the effective branch latency.

30           The microengines support deferred branches.  
Deferring branches are when a microengine allows 1 or 2  
microwords after the branch to occur before the branch



takes effect (i.e. the effect of the branch is "deferred" in time). Thus, if useful work can be found to fill the wasted cycles after the branch microword, then the branch latency can be hidden. A 1-cycle deferred branch is shown below where n2 is allowed to execute after cb, but before b1:

		1	2	3	4	5	6	7	8
10	-----+-----+-----+-----+-----+-----+-----+-----								
	microstore lookup	n1	cb	n2	XX	b1	b2	b3	b4
	reg addr gen		n1	cb	n2	XX	b1	b2	b3
	reg file lookup			n1	cb	n2	XX	b1	b2
	ALU/shifter/cc				n1	cb	n2	XX	b1
15	write back					n1	cb	n2	XX

A 2-cycle deferred branch is shown below, where n2 and n3 are both allowed to complete before the branch to b1 occurs. Note that a 2-cycle branch deferment is only allowed when the condition codes are set on the microword preceding the branch.

		1	2	3	4	5	6	7	8	9
25	-----+-----+-----+-----+-----+-----+-----+-----									
	microstore lookup	n1	cb	n2	n3	b1	b2	b3	b4	b5
	reg addr gen		n1	cb	n2	n3	b1	b2	b3	b4
	reg file lkup			n1	cb	n2	n3	b1	b2	b3
	ALU/shftr/cc				n1	cb	n2	n3	b1	b2
30	write back					n1	cb	n2	n3	b1

The microengines also support condition code evaluation. If the condition codes upon which a branch

decision are made are set 2 or more microwords before the branch, then 1 cycle of branch latency can be eliminated because the branch decision can be made 1 cycle earlier:

5		1   2   3   4   5   6   7   8
		-----+-----+-----+-----+-----+-----+-----+-----+
	microstore lookup	n1   n2   cb   XX   b1   b2   b3   b4
	reg addr gen	n1   n2   cb   XX   b1   b2   b3
	reg file lookup	n1   n2   cb   XX   b1   b2
10	ALU/shifter/cc	n1   n2   cb   XX   b1
	write back	n1   n2   cb   XX

In this example, n1 sets the condition codes and n2 does not set the conditions codes. Therefore, the branch decision can be made at cycle 4 (rather than 5), to eliminate 1 cycle of branch latency. In the example below, the 1-cycle branch deferment and early setting of condition codes are combined to completely hide the branch latency:

20 Condition codes (cc's) set 2 cycles before a 1-cycle deferred branch:

		1   2   3   4   5   6   7   8
		-----+-----+-----+-----+-----+-----+-----+-----+
25	microstore lookup	n1   n2   cb   n3   b1   b2   b3   b4
	reg addr gen	n1   n2   cb   n3   b1   b2   b3
	reg file lookup	n1   n2   cb   n3   b1   b2
	ALU/shifter/cc	n1   n2   cb   n3   b1
	write back	n1   n2   cb   n3

30

In the case where the condition codes cannot be set early (i.e. they are set in the microword preceding the branch), the microengine supports branch guessing which attempts to reduce the 1 cycle of exposed branch latency that remains. By "guessing" the branch path or the sequential path, the microsequencer pre-fetches the guessed path 1 cycle before it definitely knows what path to execute. If it guessed correctly, 1 cycle of branch latency is eliminated as shown below:

10

guess branch taken /branch is taken

15

	1	2	3	4	5	6	7	8
microstore lookup	n1	cb	n1	b1	b2	b3	b4	b5
reg addr gen		n1	cb	XX	b1	b2	b3	b4
reg file lookup			n1	cb	XX	b1	b2	b3
ALU/shifter/cc				n1	cb	XX	b1	b2
write back					n1	cb	XX	b1

20

If the microcode guessed a branch taken incorrectly, the microengine still only wastes 1 cycle:

guess branch taken /branch is NOT taken

25

30

	1	2	3	4	5	6	7	8
microstore lookup	n1	cb	n1	XX	n2	n3	n4	n5
reg addr gen		n1	cb	n1	XX	n2	n3	n4
reg file lookup			n1	cb	n1	XX	n2	n3
ALU/shifter/cc				n1	cb	n1	XX	n2
write back					n1	cb	n1	XX

However, the latency penalty is distributed differently when microcode guesses a branch is not taken:

For guess branch NOT taken / branch is NOT taken there are no wasted cycles as set out below.

5

		1	2	3	4	5	6	7	8
		-----+-----+-----+-----+-----+-----+-----+-----							
	microstore lookup	n1	cb	n1	n2	n3	n4	n5	n6
	reg addr gen		n1	cb	n1	n2	n3	n4	n5
10	reg file lookup			n1	cb	n1	n2	n1	b4
	ALU/shifter/cc				n1	cb	n1	n2	n3
	write back					n1	cb	n1	n2

However for guess branch NOT taken /branch is taken there are 2 wasted cycles.

		1	2	3	4	5	6	7	8
		-----+-----+-----+-----+-----+-----+-----+-----							
	microstore lookup	n1	cb	n1	XX	b1	b2	b3	b4
20	reg addr gen		n1	cb	XX	XX	b1	b2	b3
	reg file lookup			n1	cb	XX	XX	b1	b2
	ALU/shifter/cc				n1	cb	XX	XX	b1
	write back					n1	cb	XX	XX

25 The microengine can combine branch guessing with 1-cycle branch deferment to improve the result further. For guess branch taken with 1-cycle deferred branch/branch is taken is:

		1	2	3	4	5	6	7	8
		-----+-----+-----+-----+-----+-----+-----+-----							
	microstore lookup	n1	cb	n2	b1	b2	b3	b4	b5
	reg addr gen	n1	cb	n2	b1	b2	b3	b4	
5	reg file lookup		n1	cb	n2	b1	b2	b3	
	ALU/shifter/cc			n1	cb	n2	b1	b2	
	write back				n1	cb	n2	b1	

In the case above, the 2 cycles of branch latency  
 10 are hidden by the execution of n2, and by correctly  
 guessing the branch direction. If microcode guesses  
 incorrectly, 1 cycle of branch latency remains exposed as  
 shown below:

15           guess branch taken with 1-cycle deferred  
             branch/branch is NOT taken

		1	2	3	4	5	6	7	8	9
		-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+	-----+
20	microstore lookup	n1	cb	n2	XX	n3	n4	n5	n6	n7
	reg addr gen		n1	cb	n2	XX	n3	n4	n5	n6
	reg file lkup			n1	cb	n2	XX	n3	n4	n5
	ALU/shftr/cc				n1	cb	n2	XX	n3	n4
	write back					n1	cb	n2	XX	n3

25           If microcode correctly guesses a branch NOT  
             taken, then the pipeline flows sequentially in the normal  
             unperturbed case. If microcode incorrectly guesses branch  
             NOT taken, the microengine again exposes 1 cycle of  
 30           unproductive execution as shown below:

guess branch NOT taken/branch is taken

		1	2	3	4	5	6	7	8	9
		-----+-----+-----+-----+-----+-----+-----+-----+-----								
5	microstore lookup	n1	cb	n2	XX	b1	b2	b3	b4	b5
	reg addr gen		n1	cb	n2	XX	b1	b2	b3	b4
	reg file lkup			n1	cb	n2	XX	b1	b2	b3
	ALU/shftr/cc				n1	cb	n2	XX	b1	b2
	write back					n1	cb	n2	XX	b1

10

where nx is pre-branch microword (n1 sets cc's)

cb is conditional branch

bx is post-branch microword

XX is aborted microword

- 15 In the case of a jump instruction, 3 extra cycles of latency are incurred because the branch address is not known until the end of the cycle in which the jump is in the ALU stage:

		1	2	3	4	5	6	7	8	9
		-----+-----+-----+-----+-----+-----+-----+-----+-----								
20	microstore lookup	n1	jp	XX	XX	XX	j1	j2	j3	j4
	reg addr gen		n1	jp	XX	XX	XX	j1	j2	j3
	reg file lkup			n1	jp	XX	XX	XX	j1	j2
25	ALU/shftr/cc				n1	jp	XX	XX	XX	j1
	write back					n1	jp	XX	XX	XX

### Context Switch:

- Referring to FIG. 3B, a format from a context switch instruction is shown. A context switch is a special form of a branch that causes a different context (and associated PC) to be selected. Context switching introduces some branch latency as well. Consider the

following context switch:

		1	2	3	4	5	6	7	8	9
5	microstore lookup	ol	ca	br	n1	n2	n3	n4	n5	n6
	reg addr gen		ol	ca	XX	n1	n2	n3	n4	n5
	reg file lkup			ol	ca	XX	n1	n2	n3	n4
	ALU/shftr/cc				ol	ca	XX	n1	n2	n3
	write back					ol	ca	XX	n1	n2

10

where ox is old context flow

br is branch microword in old context

ca is context rearbitration (causes context switch)

15

nx is new context flow

XX is aborted microword

20 In a context switch the Abr@ microword is aborted to avoid control and timing complexities that could be caused by saving the correct old context PC.

Conditional branches that operate on ALU condition codes which are set on the microword before the branch can select 0, 1 or 2-cycle branch deferment modes.

25 Condition codes set 2 or more microwords before the conditional branch that operates on them can select 0 or 1-cycle branch deferment modes. All other branches (including context rearbitrations) can select either 0 or 1-cycle branch deferment modes. The architecture could be

30 designed to make a context arbitration microword within a branch deferment window of a preceding branch, jump or context arbitration microword, an illegal option. That is,

in some embodiments, a context switch would not be allowed to occur during a branch transition in the pipeline because as mentioned, it could unduly complicate saving of the old context PC. The architecture could also be designed to  
5 make branching within the branch deferment window of a preceding branch, jump or context arbitration microword illegal to avoid complicated and possible unpredictable branch behaviors.

Each microengine 22a-22f supports multi-threaded  
10 execution of four contexts. One reason for this is to allow one thread to start executing just after another thread issues a memory reference and must wait until that reference completes before doing more work. This behavior is critical to maintaining efficient hardware execution of  
15 the microengines because memory latency is significant. Stated differently, if only a single thread execution was supported, the microengines would sit idle for a significant number of cycles waiting for references to return and thereby reduce overall computational throughput.  
20 Multi-threaded execution allows an microengines to hide memory latency by performing useful independent work across several threads. Two synchronization mechanisms are supplied in order to allow a thread to issue an SRAM or SDRAM reference, and then subsequently synchronize to the  
25 point in time when that reference completes.

One mechanism is Immediate Synchronization. In immediate synchronization, the microengine issues the reference and immediately swap out that context. The context will be signaled when the corresponding reference  
30 completes. Once signaled, the context will be swapped back



in for execution when a context-swap event occurs and it is  
its turn to run. Thus, from the point of view of a single  
context's instruction stream, the microword after issuing  
the mem reference does not get executed until the reference  
5 completes.

A second mechanism is Delayed Synchronization.  
In delayed synchronization, the microengine issues the  
reference, and then continues to execute some other useful  
work independent of the reference. Some time later it  
10 could become necessary to synchronize the thread's  
execution stream to the completion of the issued reference  
before further work is performed. At this point a  
synchronizing microword is executed that will either swap  
out the current thread, and swap it back in sometime later  
15 when the reference has completed, or continue executing the  
current thread because the reference has already completed.  
Delayed synchronization is implemented using two different  
signaling schemes:

If the memory reference is associated with a  
20 transfer register, the signal from which the thread is  
triggered is generated when the corresponding transfer  
register valid bit is set or cleared. For example, an SRAM  
read which deposits data into transfer register A would be  
signaled when the valid bit for A is set. If the memory  
25 reference is associated with the transfer FIFO or the  
receive FIFO, instead of a transfer register, then the  
signal is generated when the reference completes in the  
SDRAM controller 26a. Only one signal state per context is  
held in the microengines scheduler, thus only one  
30 outstanding signal can exist in this scheme.

There are at least two general operational paradigms from which microcontroller micro-programs could be designed. One would be that overall microcontroller compute throughput and overall memory bandwidth are  
5 optimized at the expense of single thread execution latency. This paradigm would make sense when the system has multiple microengines executing multiple threads per microengine on unrelated data packets.

A second one is that microengine execution  
10 latency should be optimized at the expense of overall microengine compute throughput and overall memory bandwidth. This paradigm could involve execution of a thread with a real-time constraint, that is, a constraint which dictates that some work must absolutely be done by  
15 some specified time. Such a constraint requires that optimization of the single thread execution be given priority over other considerations such as memory bandwidth or overall computational throughput. A real-time thread would imply a single microengine that executes only one  
20 thread. Multiple threads would not be handled because the goal is to allow the single real-time thread to execute as soon as possible--execution of multiple threads would hinder this ability.

The coding style of these two paradigms could be  
25 significantly different with regard to issuing memory references and context switching. In the real time case, the goal is to issue as many memory references as soon as possible in order to minimize the memory latency incurred by those references. Having issued as many references as  
30 early as possible the goal would be to perform as many

computations as the microengines as possible in parallel with the references. A computation flow that corresponds to real-time optimization is:

- 5       o) issue mem ref 1
- o) issue mem ref 2
- o) issue mem ref 3
- o) perform work independent of mem refs 1, 2 and 3
- o) synch to completion of mem ref 1
- 10      o) perform work dependent on mem ref 1 and independent of mem ref 2
- and 3
- o) issue any new mem refs based on preceding work.
- o) synch to completion of mem ref 2
- o) perform work dependent on mem ref 1 and 2 independent of mem ref
- 15      3
- o) issue any new mem refs based on preceding work.
- o) synch to completion of mem ref 3
- o) perform work dependent on the completion of all 3 refs
- o) issue any new mem refs based on preceding work.

20

In contrast, optimization for throughput and bandwidth would take a different approach. With optimization for microengine computational throughput and overall memory bandwidth less consideration is given to

25 single thread execution latency. To accomplish this, the goal would be to equally space memory references across the microprogram for each thread. This would provide a uniform stream of memory references to the SRAM and SDRAM controllers and would maximize the probability that 1

30 thread is always available to hide the memory latency incurred when another thread is swapped out.

Register file address types:

Referring to FIG. 3C, the two register address spaces that exist are Locally accessible registers, and Globally accessible registers accessible by all microengines. The General Purpose Registers (GPRs) are implemented as two separate banks (A bank and B bank) whose addresses are interleaved on a word-by-word basis such that A bank registers have lsb=0, and B bank registers have lsb=1. Each bank is capable of performing a simultaneous read and write to two different words within its bank.

Across banks A and B, the register set 76b is also organized into four windows 76b<sub>0</sub>-76b<sub>3</sub> of 32 registers that are relatively addressable per thread. Thus, thread<sub>0</sub> will find its register 0 at 77a (register 0), the thread<sub>1</sub> will find its register<sub>0</sub> at 77b (register 32), thread<sub>2</sub> will find its register<sub>0</sub> at 77c (register 64), and thread<sub>3</sub> at 77d (register 96). Relative addressing is supported so that multiple threads can use the exact same control store and locations but access different windows of register and perform different functions. The uses of register window addressing and bank addressing provide the requisite read bandwidth using only dual ported RAMS in the microengine 22f.

These windowed registers do not have to save data from context switch to context switch so that the normal push and pop of a context swap file or stack is eliminated. Context switching here has a 0 cycle overhead for changing from one context to another. Relative register addressing divides the register banks into windows across the address width of the general purpose register set. Relative

addressing allows access any of the windows relative to the starting point of the window. Absolute addressing is also supported in this architecture where any one of the absolute registers may be accessed by any of the threads by providing the exact address of the register.

Addressing of general purpose registers 78 can occur in 2 modes depending on the microword format. The two modes are absolute and relative. In absolute mode, addressing of a register address is directly specified in 7-bit source field (a6-a0 or b6-b0):

	7	6	5	4	3	2	1	0	
	+-----+-----+-----+-----+-----+								
A GPR:	a6	0	a5	a4	a3	a2	a1	a0	a6=0
B GPR:	b6	1	b5	b4	b3	b2	b1	b0	b6=0
SRAM/ASB:	a6	a5	a4	0	a3	a2	a1	a0	a6=1, a5=0, a4=0
SDRAM:	a6	a5	a4	0	a3	a2	a1	a0	a6=1, a5=0, a4=1

register address directly specified in 8-bit dest field (d7-d0):

	7	6	5	4	3	2	1	0	
	+-----+-----+-----+-----+-----+								
A GPR:	d7	d6	d5	d4	d3	d2	d1	d0	d7=0, d6=0
B GPR:	d7	d6	d5	d4	d3	d2	d1	d0	d7=0, d6=1
SRAM/ASB:	d7	d6	d5	d4	d3	d2	d1	d0	d7=1, d6=0, d5=0
SDRAM:	d7	d6	d5	d4	d3	d2	d1	d0	d7=1, d6=0, d5=1

If <a6:a5>=1,1, <b6:b5>=1,1, or <d7:d6>=1,1 then the lower bits are interpreted as a context-relative address field (described below). When a non-relative A or B source address is specified in the A, B absolute field, only the lower half of the SRAM/ASB and SDRAM address

spaces can be addressed. Effectively, reading absolute  
 SRAM/SDRAM devices has the effective address space;  
 however, since this restriction does not apply to the dest  
 field, writing the SRAM/SDRAM still uses the full address  
 5 space.

In relative mode, addresses a specified address  
 is offset within context space as defined by a 5-bit source  
 field (a4-a0 or b4-b0):

```

      7 6 5 4 3 2 1 0
      +---+---+---+---+---+---+
10    A GPR: | a4| 0 |context| a3| a2| a1| a0| a4=0
      B GPR: | b4| 1 |context| b3| b2| b1| b0| b4=0
      SRAM/ASB: |ab4| 0 |ab3|context| b2| b1|ab0| ab4=1, ab3=0
      SDRAM:   |ab4| 0 |ab3|context| b2| b1|ab0| ab4=1, ab3=1

```

or as defined by the 6-bit dest field (d5-d0):

```

      7 6 5 4 3 2 1 0
      +---+---+---+---+---+---+
20    A GPR: | d5| d4|context| d3| d2| d1| d0| d5=0, d4=0
      B GPR: | d5| d4|context| d3| d2| d1| d0| d5=0, d4=1
      SRAM/ASB: | d5| d4| d3|context| d2| d1| d0| d5=1, d4=0, d3=0
      SDRAM:   | d5| d4| d3|context| d2| d1| d0| d5=1, d4=0, d3=1

```

25 If <d5:d4>=1,1, then the destination address does  
 not address a valid register, thus, no dest operand is  
 written back.

The following registers are globally accessible  
 from the microengines and the memory controllers:

```

30    hash unit registers
      scratchpad and common registers
      receive FIFO and receive status FIFO

```

transmit FIFO

transmit control FIFO

The microengines are not interrupt driven. Each microflow executes until completion and then a new flow is chosen based on state signaled by other devices in the processor 12.

Referring to FIG. 4, the SDRAM memory controller 26a includes memory reference queues 90 where memory reference requests arrive from the various microengines 22a-22f. The memory controller 26a includes an arbiter 91 that selects the next the microengine reference requests to go to any of the functioning units. Given that one of the microengines is providing a reference request, the reference request will come through the address and command queue 90, inside the SDRAM controller 26a. If the reference request has a bit set called the Aoptimized MEM bit@ the incoming reference request will be sorted into either the even bank queue 90a or the odd bank queue 90b. If the memory reference request does not have a memory optimization bit set, the default will be to go into an order queue 90c. The SDRAM controller 26 is a resource which is shared among the FBUS interface 28, the core processor 20 and the PCI interface 24. The SDRAM controller 26 also maintains a state machine for performing READ-MODIFY-Write atomic operations. The SDRAM controller 26 also performs byte alignment for requests of data from SDRAM.

The order queue 90c maintains the order of reference requests from the microengines. With a series of

odd and even banks references it may be required that a

signal is returned only upon completion of a sequence of memory references to both the odd and even banks. If the microengine 22f sorts the memory references into odd bank and even bank references and one of the banks, e.g., the even bank is drained of memory references before the odd bank but the signal is asserted on the last even reference, the memory controller 26a could conceivably signal back to a microengine that the memory request had completed, even though the odd bank reference had not been serviced. This occurrence could cause a coherency problem. The situation is avoided by providing the order queue 90c allowing a microengine to have multiple memory references outstanding of which only its last memory reference needs to signal a completion.

The SDRAM controller 26a also includes a high priority queue 90d. In the high priority queue 90d, an incoming memory reference from one of the microengines goes directly to the high priority queue and is operated upon at a higher priority than other memory references in the other queues. All of these queues, the even bank queue 90a, the odd bank queue 90b, the order queue 90c and the high priority queue, are implemented in a single RAM structure that is logically segmented into four different windows, each window having its own head and tail pointer. Since filling and draining operations are only a single input and a single output, they can be placed into the same RAM structure to increase density of RAM structures.

The SDRAM controller 26a also includes core bus interface logic i.e., ASB bus 92. The ASB bus interface

logic 92 interfaces the core processor 20 to the SDRAM



controller 26a. The ASB bus is a bus that includes a 32 bit data path and a 28 bit address path. The data is accessed to and from memory through MEM ASB data device 98, e.g., a buffer. MEM ASB data device 98 is a queue for  
5 write data. If there is incoming data from the core processor 20 via ASB interface 92, the data can be stored into the MEM ASB device 98 and subsequently removed from MEM ASB device 98 through the SDRAM interface 110 to SDRAM memory 16a. Although not shown, the same queue structure  
10 can be provided for the reads. The SDRAM controller 26a also includes an engine 97 to pull data from the microengines and PCI bus.

Additional queues include the PCI address queue 94 and ASB read/write queue 96 that maintain a number of  
15 requests. The memory requests are sent to SDRAM interface 110 via multiplexer 106. The multiplexer 106 is controlled by the SDRAM arbiter 91 which detects the fullness of each of the queues and the status of the requests and from that decides priority based on a programmable value stored in a  
20 priority service control register 100.

Once control to the multiplexer 106 selects a memory reference request, the memory reference request, is sent to a decoder 108 where it is decoded and an address is generated. The decoded address is sent to the SDRAM  
25 interface 110 where it is decomposed into row and column address strobes to access the SDRAM 16a and write or read data over data lines 16a sending data to bus 112. In one implementation, bus 112 is actually two separate buses instead of a single bus. The separate buses would include  
30 a read bus coupling the distributed microengines 22a-22f

and a write bus coupling the distributed microengines 22a-22f.

A feature of the SDRAM controller 26a is that when a memory reference is stored in the queues 90, in addition to the optimized MEM bit that can be set, there is a chaining bit. The chaining bit when set allows for special handling of contiguous memory references. As previously mentioned, the arbiter 12 controls which microengine will be selected to provide memory reference requests over the commander bus to queue 90 (FIG. 4). Assertion of the chain bit will control the arbiter to have the arbiter select the functional unit which previously requested that bus because setting of the chain bit indicates that the microengine issued a chain request.

Contiguous memory references will be received in queue 90 when the chaining bit is set. Those contiguous references will typically be stored in the order queue 90c because the contiguous memory references are multiple memory references from a single thread. In order to provide synchronization, the memory controller 26a need only signal at the end of the chained memory references when done. However, in an optimized memory chaining, (e.g, when optimized MEM bit and chaining bit are set) the memory references could go into different banks and potentially complete on one of the banks issuing the signal Adone before the other bank was fully drained, thus destroying coherency. Therefore, the chain bit is used by the controller 110 to maintain the memory references from the current queue.

30

Referring to FIG. 4A, a flow representation of the arbitration policy in the SDRAM controller 26a is shown. The arbitration policy favors chained microengine memory requests. The process 115 starts by examining for

5 Chained microengine memory reference requests 115a. The process 115 stays at the chained requests until the chain bit is cleared. The process examines ASB bus requests 115b followed by PCI bus requests 115c, High Priority Queue Service 115d, Opposite Bank Requests 115e, Order Queue

10 Requests 115f, and Same Bank Requests 115g. Chained request are serviced completely, whereas services 115b-115d are serviced in round robin order. Only when services 115a-115d are fully drained does the process handle services 115e-115g. Chained microengine memory reference

15 requests are when the previous SDRAM memory request has the chain bit set. When the chain bit is set then the arbitration engine simply services the same queue again, until the chain bit is cleared. The ASB is higher priority than PCI due to the severe performance penalty imposed on

20 the Strong arm core when the ASB is in wait state. PCI has higher priority than the microengines due to the latency requirements of PCI. However with other buses, the arbitration priority could be different.

As shown in FIG. 4B, typical timing of a memory

25 without active memory optimization and with active memory optimization is shown. As can be seen, the use of active memory optimizations maximizes the use of the bus and thus

hides the inherent latency within physical SDRAM devices. In this example, a non-optimized access can take 14 cycles while optimized access can take 7 cycles.

Referring to FIG. 5, the memory controller 26b for the SRAM is shown. The memory controller 26b includes an address and command queue 120. While the memory controller 26a (FIG. 4) has a queue for memory optimization based on odd and even banking, memory controller 26b is optimized based on the type of memory operation, i.e., a read or a write. The address and command queue 120 includes a high priority queue 120a, a read queue 120b which is the predominant memory reference function that an SRAM performs, and an order queue 120c which in general will include all writes to SRAM and reads that are to be non-optimized. Although not shown, the address and command queue 120 could also include a write queue.

The SRAM controller 26b also includes core bus interface logic i.e., ASB bus 122. The ASB bus interface logic 122 interfaces the core processor 20 to the SRAM controller 26b. The ASB bus is a bus that includes a 32 bit data path and a 28 bit address path. The data is accessed to and from memory through MEM ASB data device 128, e.g., a buffer. MEM ASB data device 128 is a queue for write data. If there is incoming data from the core processor 20 via ASB interface 122, the data can be stored into the MEM ASB device 128 and subsequently removed from MEM ASB device 128 through SRAM interface 140 to SRAM memory 16b. Although not shown, the same queue structure

30

can be provided for reads. The SRAM controller 26b also includes an engine 127 to pull data from the microengines and PCI bus.

The memory requests are sent to SRAM interface 140 via multiplexer 126. The multiplexer 126 is controlled by the SRAM arbiter 131 which detects the fullness of each of the queues and the status of the requests and from that decides priority based on a programmable value stored in a priority service control register 130. Once control to the multiplexer 126 selects a memory reference request, the memory reference request, is sent to a decoder 138 where it is decoded and an address is generated. The SRAM Unit maintains control of the Memory Mapped off-chip SRAM and Expansion ROM. The SRAM controller 26b can address, e.g., 16 MBytes, with, e.g., 8 MBytes mapped for SRAM 16b, and 8 MBytes reserved for special functions including: Boot space via flashrom 16c; and Console port access for MAC devices 13a, 13b and access to associated (RMON) counters. The SRAM is used for local look-up tables and queue management functions.

The SRAM controller 26b supports the following transactions:

Microengine requests	(via private bus)	to/from SRAM.
Core Processor	(via ASB bus)	to/from SRAM.

The SRAM controller 26b performs memory reference sorting to minimize delays (bubbles) in the pipeline from the SRAM interface 140 to memory 16b. The SRAM controller 26b does memory reference sorting based on the read

function. A bubble can either be 1 or 2 cycles depending on the type of memory device employed.

The SRAM controller 26b includes a lock lookup device 142 which is an eight (8 entry address content addressable memory for look-ups of read locks. Each position include a valid bit that is examined by subsequent read-lock requests. The address and command queue 120 also includes a Read Lock Fail Queue 120d. The Read Lock Fail Queue 120d is used to hold read memory reference requests that fail because of a lock existing on a portion of memory. That is, one of the microengines issues a memory request that has a read lock request that is processed in address and control queue 120. The memory request will operate on either the order queue 120c or the read queue 120b and will recognize it as a read lock request. The controller 26b will access lock lookup device 142 to determine whether this memory location is already locked. If this memory location is locked from any prior read lock request, then this memory lock request will fail and will be stored in the read lock fail queue 120d. If it is unlocked or if 142 shows no lock on that address, then the address of that memory reference will be used by the SRAM interface 140 to perform a traditional SRAM address read/write request to memory 16b. The command controller and address generator 138 will also enter the lock into the lock look up device 142 so that subsequent read lock requests will find the memory location locked. A memory location is unlocked by operation of the a microcontrol instruction in a program after the need for the lock has ended. The location is unlocked by clearing the valid bit

in the CAM. After an unlock, the read lock fail queue 120d becomes the highest priority queue giving all queued read lock misses, a chance to issue a memory lock request.

As shown in FIG. 5A, typical timing of a static random access memory without active memory optimization and with active memory optimization is shown. As can be seen, grouping reads and writes improves cycletime eliminating dead cycles.

Referring to FIG. 6, communication between the microengines 22 and the FBUS interface Logic (FBI) is shown. The FBUS interface 28 in a network application can performs header processing of incoming packets from the FBUS 18. A key function which the FBUS interface performs is extraction of packet headers, and a microprogrammable source/destination/protocol hashed lookup in SRAM. If the hash does not successfully resolve, the packet header is promoted to the core processor 28 for more sophisticated processing.

The FBI 28 contains a Transmit FIFO 182, a Receive FIFO 183, a HASH unit 188 and FBI control and status registers 189. These four units communicate with the microengines 22, via a time-multiplexed access to the SRAM bus 38 which is connected to the transfer registers 78, 80 in the microengines. That is, all communications to and from the microengines are via the transfer registers 78, 80. The FBUS interface 28 includes a push state machine 200 for pushing data into the transfer registers during the time cycles which the SRAM is NOT using the SRAM

30

multiplexed access

data bus (part of bus 38) and a pull state machine 202 for fetching data from the transfer registers in the respective microengine.

The Hashing unit includes a pair of FIFO=s 188a, 5 188b. The hash unit determines that the FBI 28 received an FBI\_hash request. The hash unit 188 fetches hash keys from the calling microengine 22. After the keys are fetched and hashed, the indices are delivered back to the calling microengine 22. Up to three hashes are performed under a 10 single FBI\_hash request. The busses 34 and 38 are each unidirectional: SDRAM\_push/pull\_data, and Sbus\_push/pull\_data. Each of these busses require control signals which will provide read/write controls to the appropriate microengine 22 Transfer registers.

15



Generally, transfer registers require protection from the context controlling them to guarantee read correctness. In particular, if a write transfer register is being used by a thread\_1 to provide data to the SDRAM 16a, thread\_1 must not overwrite this register until the signal back from SDRAM controller 26a indicates that this register has been promoted and may now be re-used. Every write does not require a signal back from the destination indicating that the function has been completed, because if the thread writes to the same command queue at that destination with multiple requests, the order of the completion is guaranteed within that command queue, thus only the last command requires the signaling back to the thread. However, if the thread uses multiple command queues (order and read), then these command requests must be broken into separate context tasks, so that ordering is maintained via context swapping. The exception case indicated at the beginning of this paragraph is relative to a certain class of operations using an unsolicited PUSH to transfer registers from the FBI for FBUS status information. In order to protect read/write determinism on the transfer registers, the FBI provides a special Push\_protect signal when these special FBI push operations are set up.

Any microengine 22 that uses the FBI unsolicited push technique must test the protection flag prior to accessing the FBUS interface/microengine agreed upon transfer registers. If the flag is not asserted, then the transfer registers may be accessed by the microengine. If the flag is Asserted then the context should wait N cycles prior to accessing the registers. A priori this count is determined by the number of transfer registers being pushed, plus a frontend protection window. The basic idea is that the Microengine must test this flag then quickly move the data which it wishes to read from the read transfer registers to GPR's in contiguous cycles, so the push engine does not collide with the Microengine read.

#### Other Embodiments

It is to be understood that while the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

## CLAIMS

1. A controller for a random access memory comprises:

an address and command queue that holds memory  
5 references from a plurality of microcontrol functional  
units;

a first read/write queue that holds memory  
reference from a computer bus;

a second read/write queue that holds memory  
10 references from a core processor; and

control logic including an arbiter that detects  
the fullness of each of the queues and a status of  
outstanding memory reference to select a memory reference  
from one of the queues.

15

2. The controller of claim 1 wherein the control  
logic further selects one of the queues to provide a next  
memory references based on a programmable value stored in a  
priority service control register.

20

3. The controller of claim 1 wherein the address and  
command queue comprises:

a high priority queue that holds memory  
references from high priority tasks.

25

4. The controller of claim 1 wherein the address and command queue comprises:

an even bank queue;  
an odd bank queue; and

5 wherein a microengine sorts memory references into odd bank and even bank references.

5. The controller of claim 1 wherein the address and command queue comprises:

10 an order queue and wherein controller examines an optimized memory reference bit and if set, causes incoming reference requests to be sorted into either the even bank queue or the odd bank queue.

15 6. The controller of claim 5 wherein the address and command queue comprises:

an order queue; and

wherein if the memory reference request does not have a memory optimization bit set, the memory reference is  
20 stored in the order queue.

7. The controller of claim 1 wherein the address and command queue is implemented in a single memory structure and comprises:

25 an order queue for storing memory references;  
an even bank queue for storing memory references;  
an odd bank queue for storing memory references;  
a high priority queue for storing memory  
references; and

30 with the memory structure being segmented into

four different queue regions, each region having its own head and tail pointer.

8. The controller of claim 7 wherein the address and  
5 command queue further comprises:

an insert queue control and a remove queue arbitration logic to control insert and removal of memory references from the queues.

- 10 9. The controller of claim 1 further comprising:  
a command controller and address generator that is responsive to an address from a selected memory reference from one said queues, to produce addresses and commands to control a memory interface.

15

10. The controller of claim 9 further comprising:  
a memory interface responsive to generated addresses and commands to produce memory control signals.

- 20 11. The controller of claim 1 wherein the control logic is responsive to a chaining bit that when set allows for special handling of contiguous memory references.

12. The controller of claim 1 wherein assertion of  
25 the chain bit will control the arbiter to have the arbiter select the functional unit which previously requested that bus because setting of the chain bit indicates that the microengine issued a chain request.

13. The controller of claim 1 wherein the control logic is responsive to an optimized memory bit and a chaining bit, and wherein assertion of the chaining bit will control the arbiter when the optimized memory bit is also set to maintain the memory references from a current queue.

14. The controller of claim 1 wherein the arbiter has an arbitration policy that favors chained microengine memory references.

15. The controller of claim 14 wherein the arbiter has an arbitration policy that services chained requests until the chain bit is cleared.

16. The controller of claim 1 wherein the arbiter has an arbitration policy that starts by examining for chained microengine memory reference requests.

17. The controller of claim 16 wherein the arbitration policy enables chained memory requests to be serviced completely.

18. The controller of claim 16 wherein when the chain bit is set, the arbitration engine services the same queue again until the chain bit is cleared.

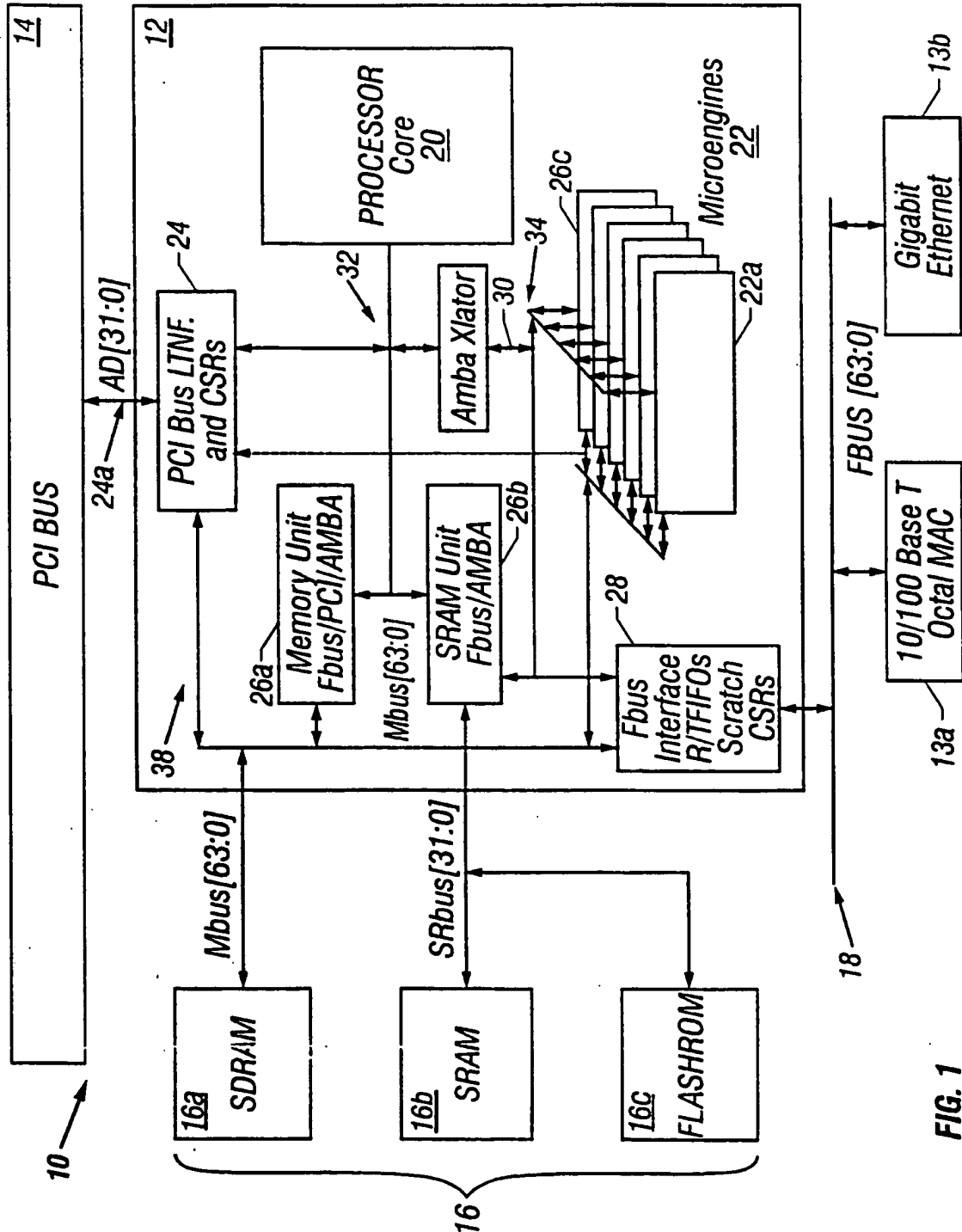


FIG. 1

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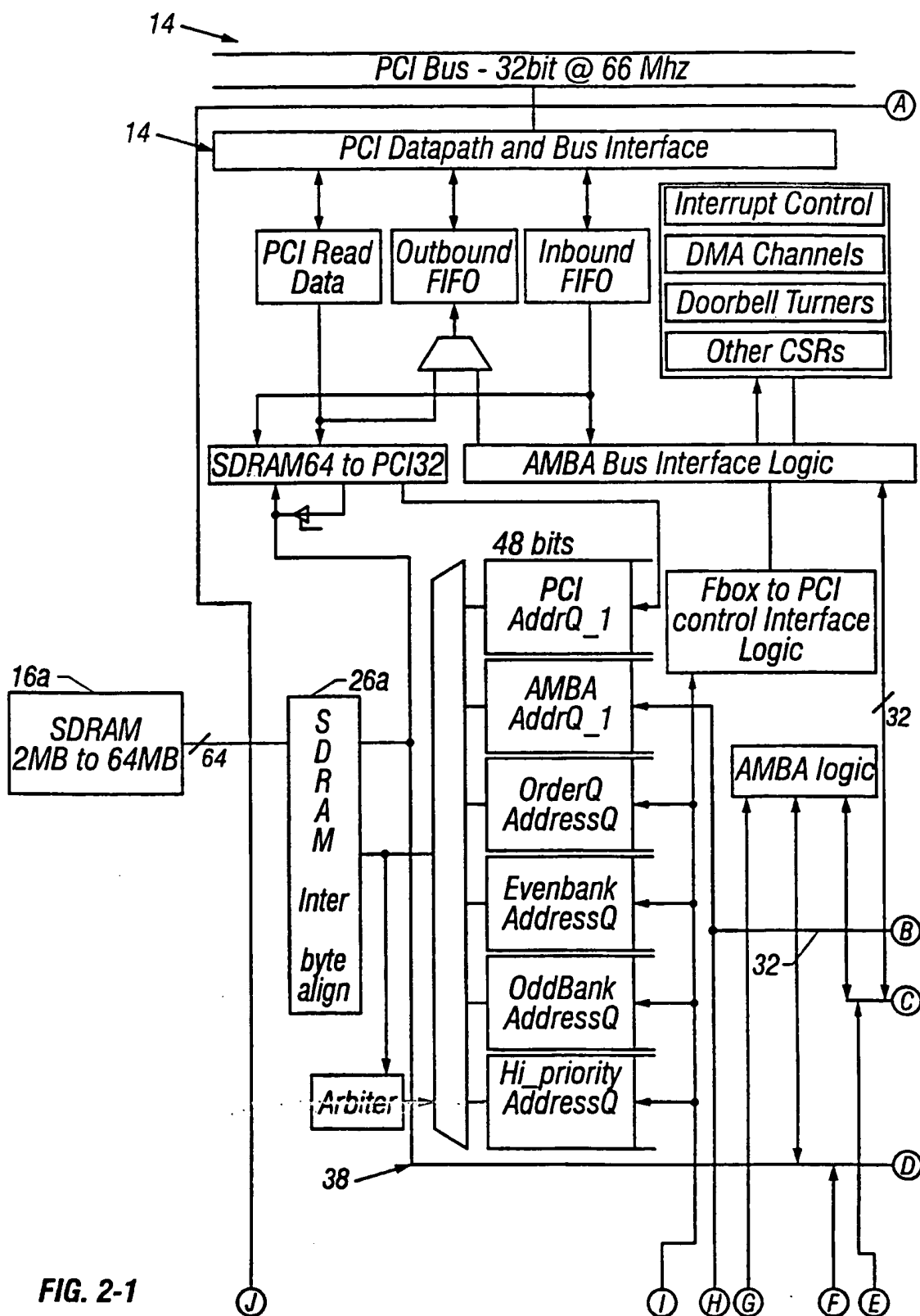


FIG. 2-1



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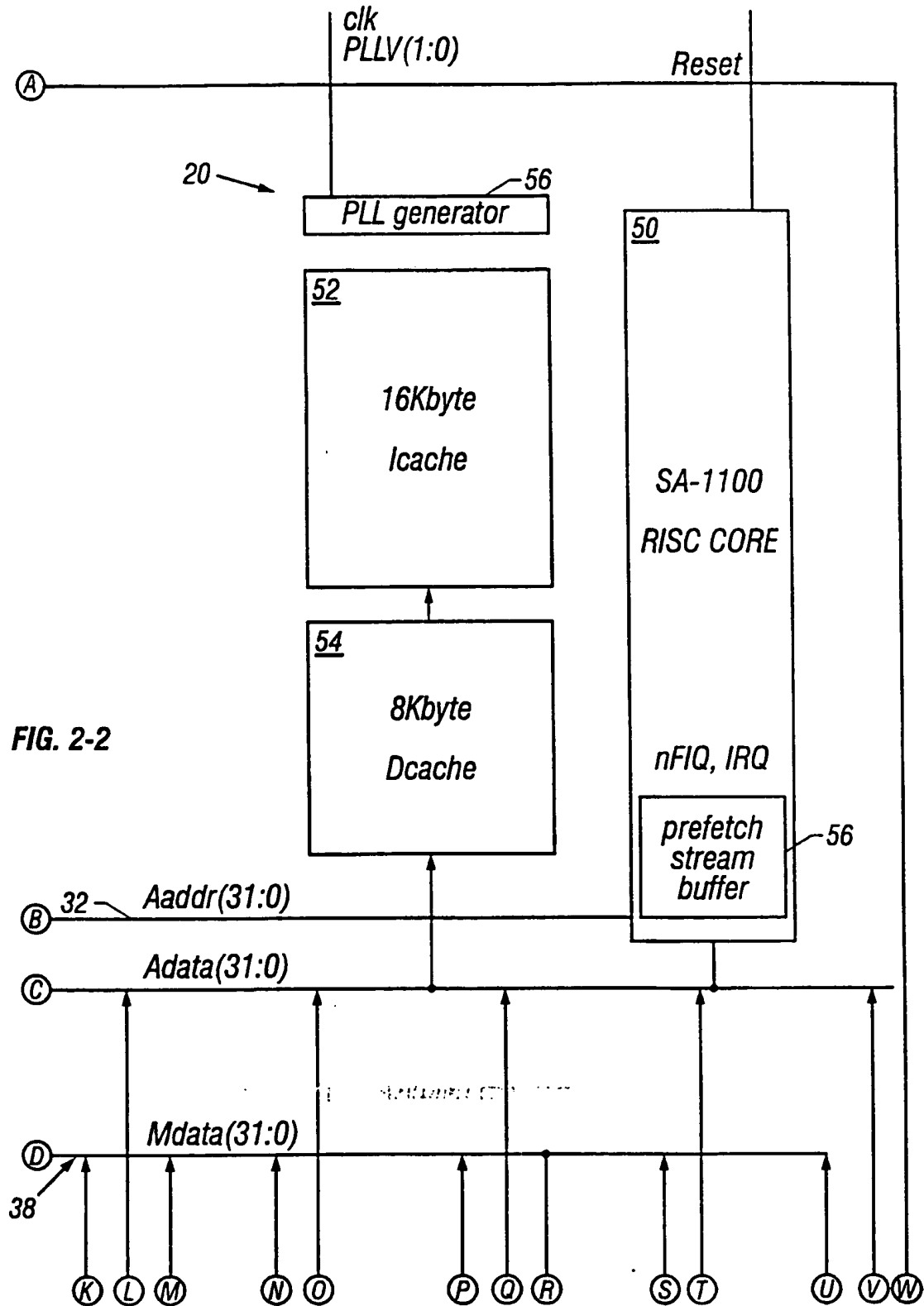


FIG. 2-2

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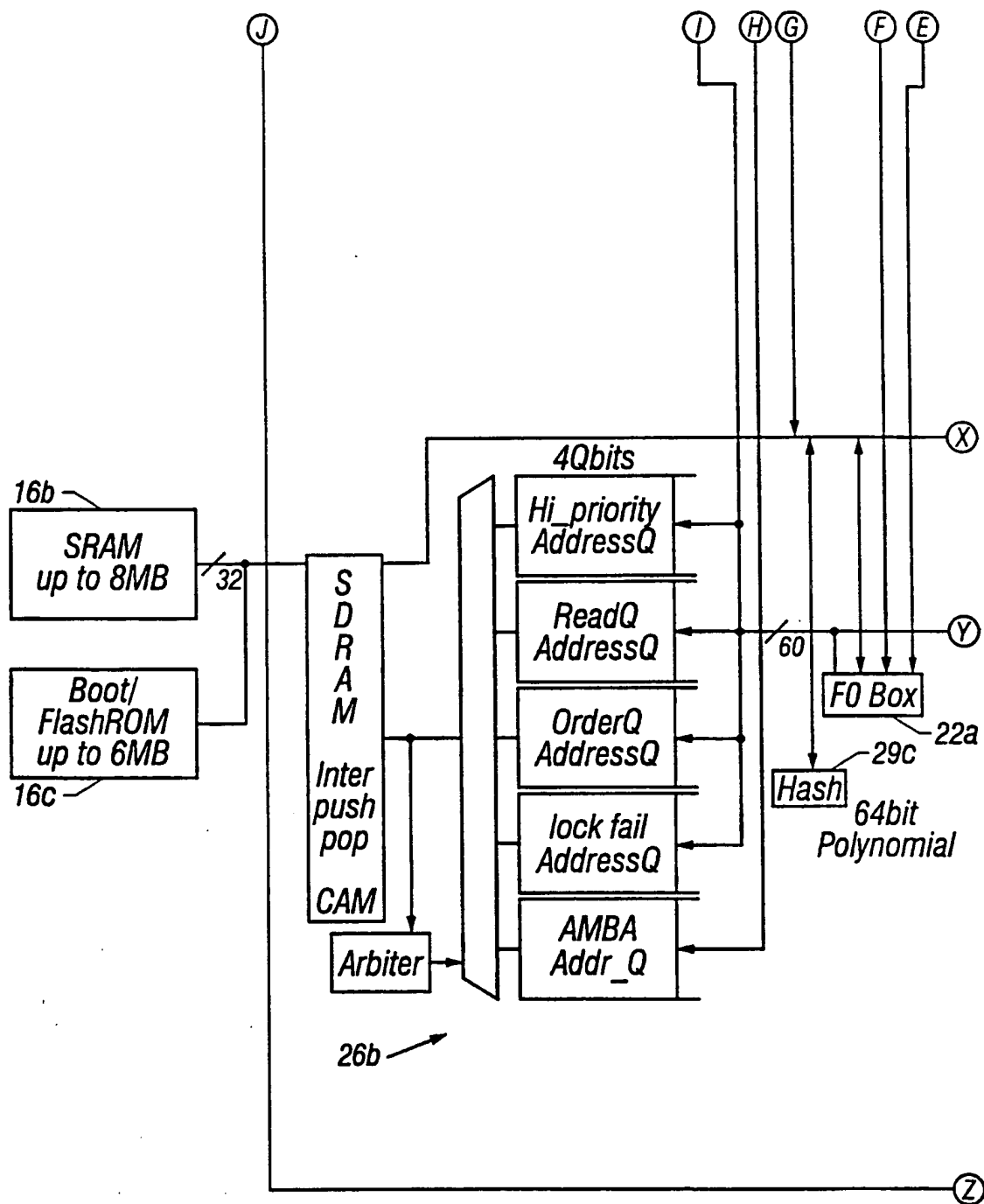


FIG. 2-3

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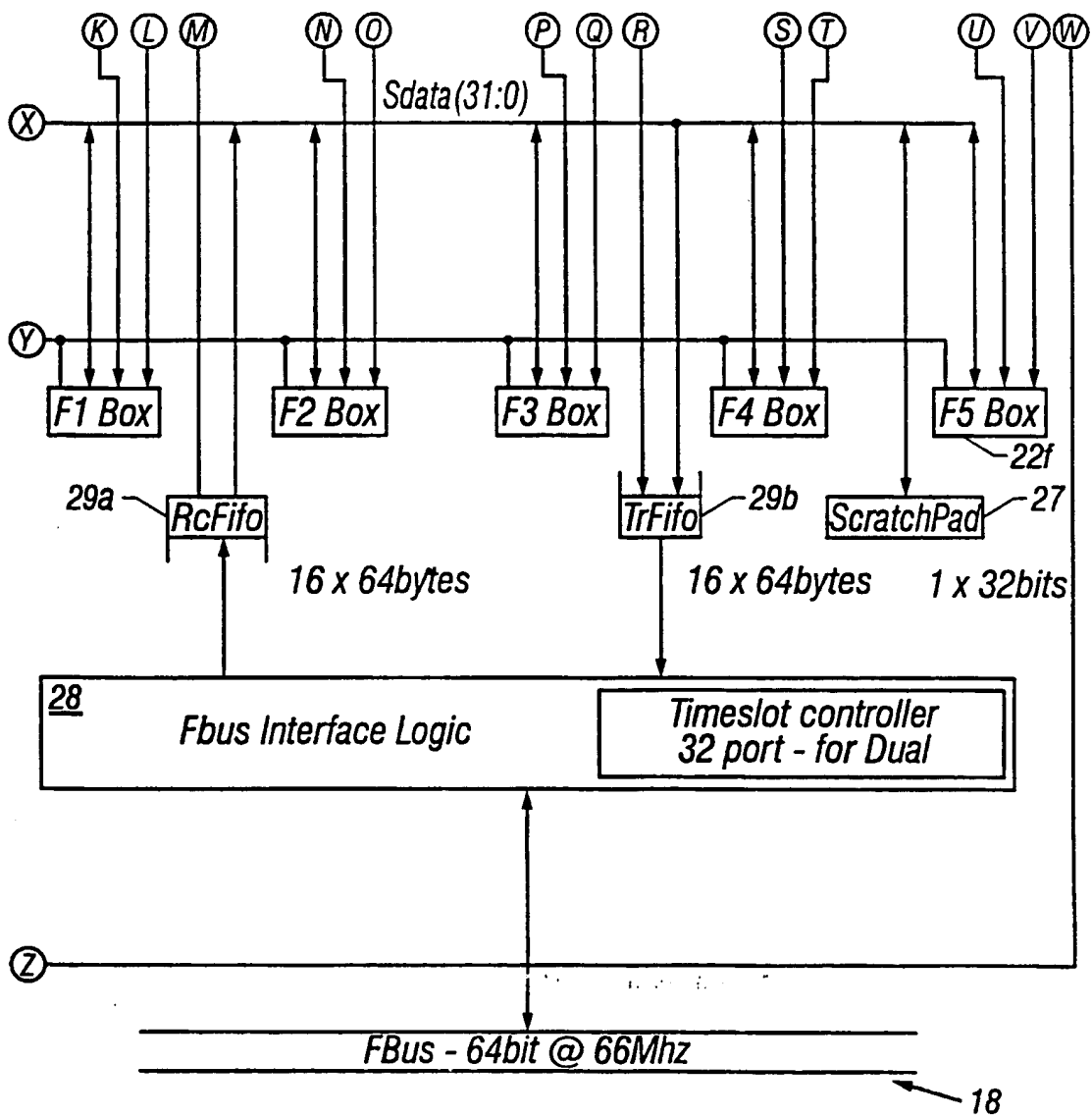


FIG. 2-4

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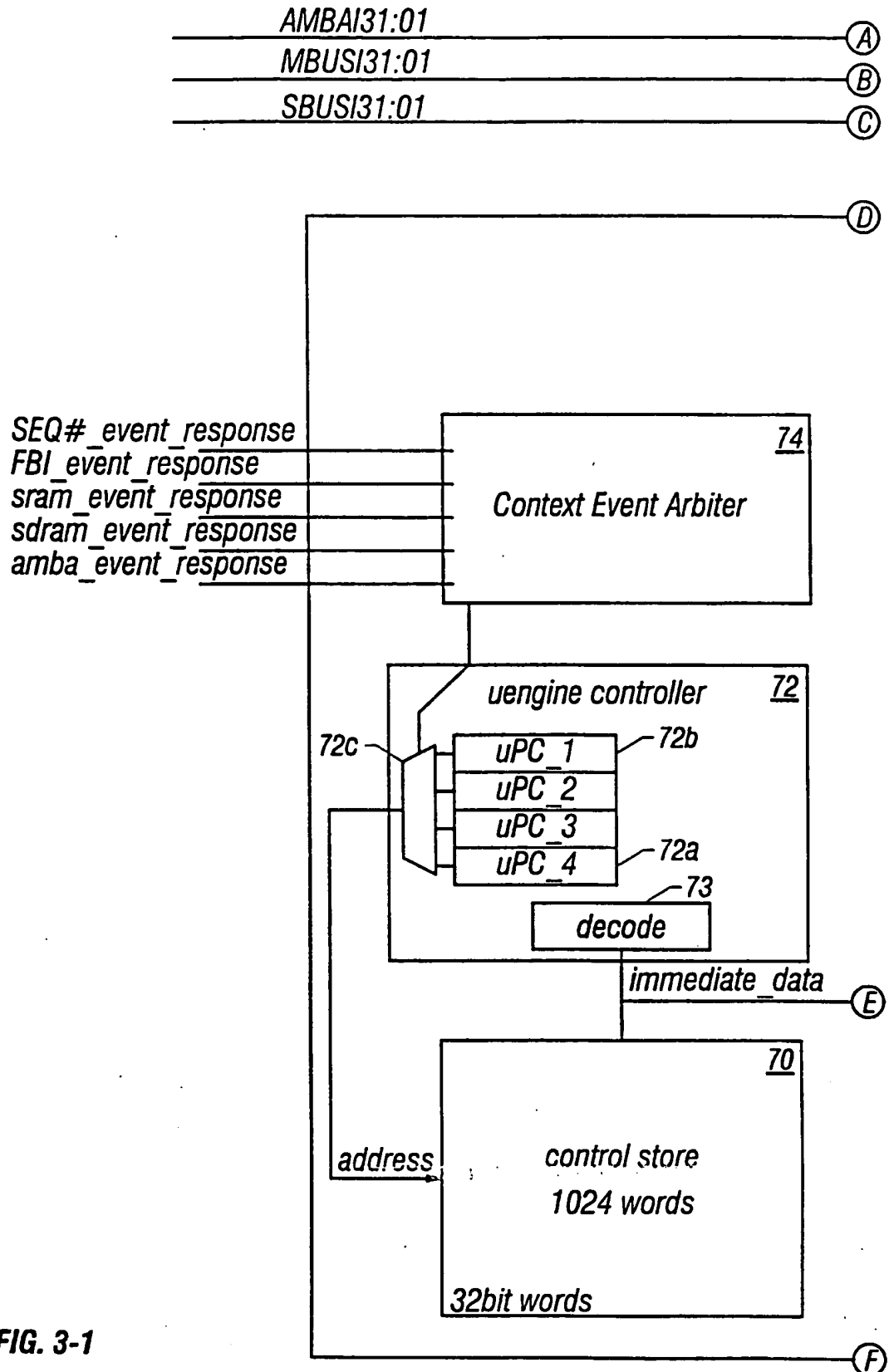


FIG. 3-1

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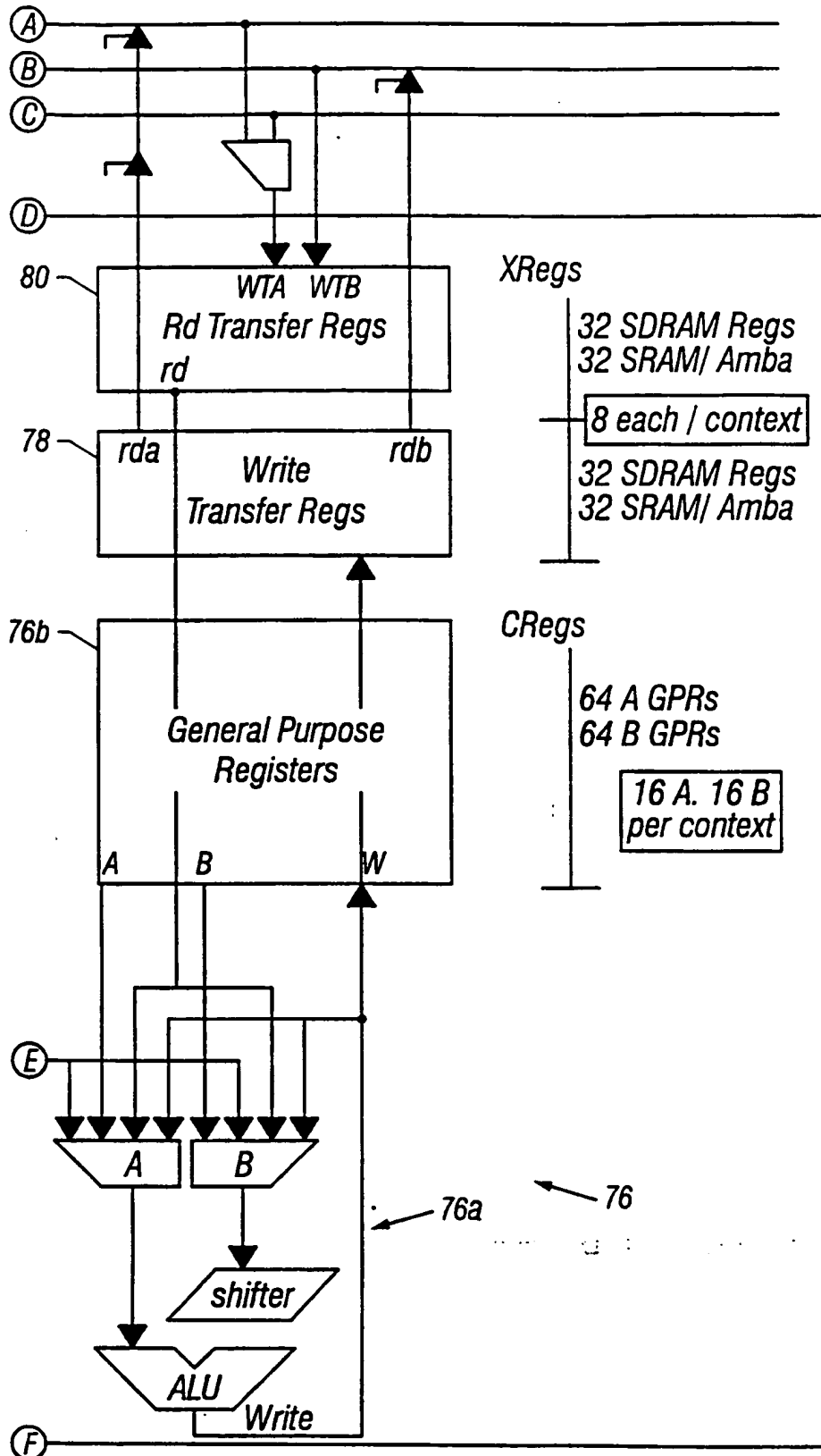


FIG. 3-2

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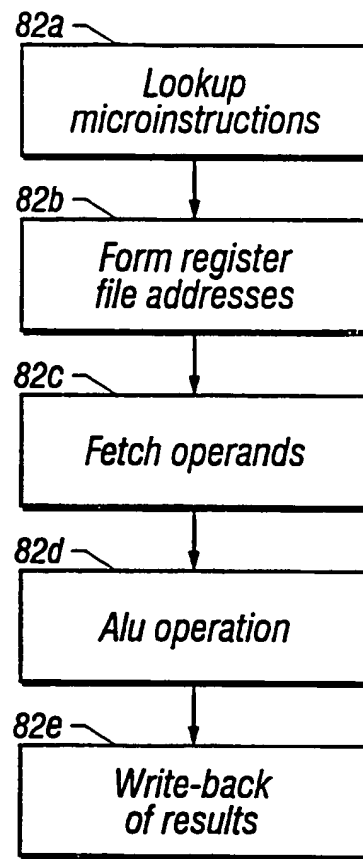


FIG. 3A

[illegible]

### 1) Wake-up Events (Bits 8-15)

**$0 = \text{kill}$**

***1 = voluntary***

## 2 = SRAM

**4 = SDRAM**

**8 = FBI**

**16 = INTER THREAD**

**32 = PCI DMA 1**

**64 = PCI\_DMA\_2**

**128 = SEQ\_NUM\_LSB**

2)  $\overline{db} \rightarrow \overline{\text{branch defer amount (Bit 17)}}$

3) *va* -> value of sequence number (Bit 7)

#### 4) *OPCODE BITS (29-31)*

5) `ext_cmd`

**FIG. 3B**

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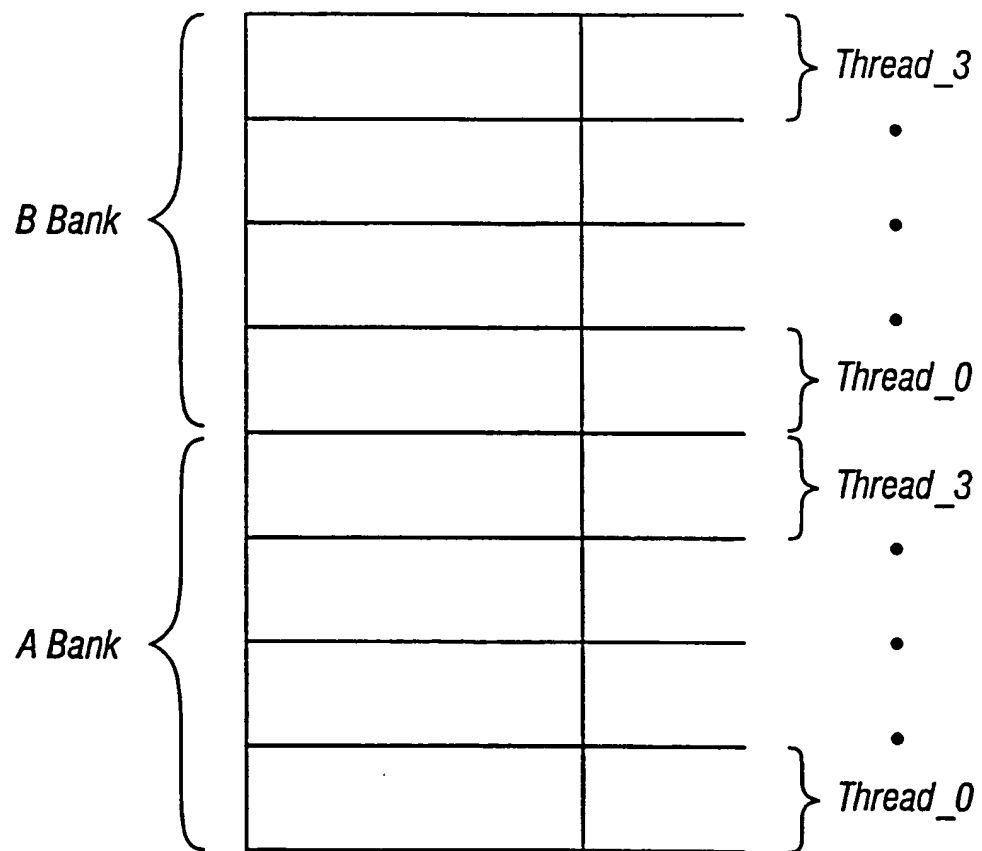


FIG. 3C



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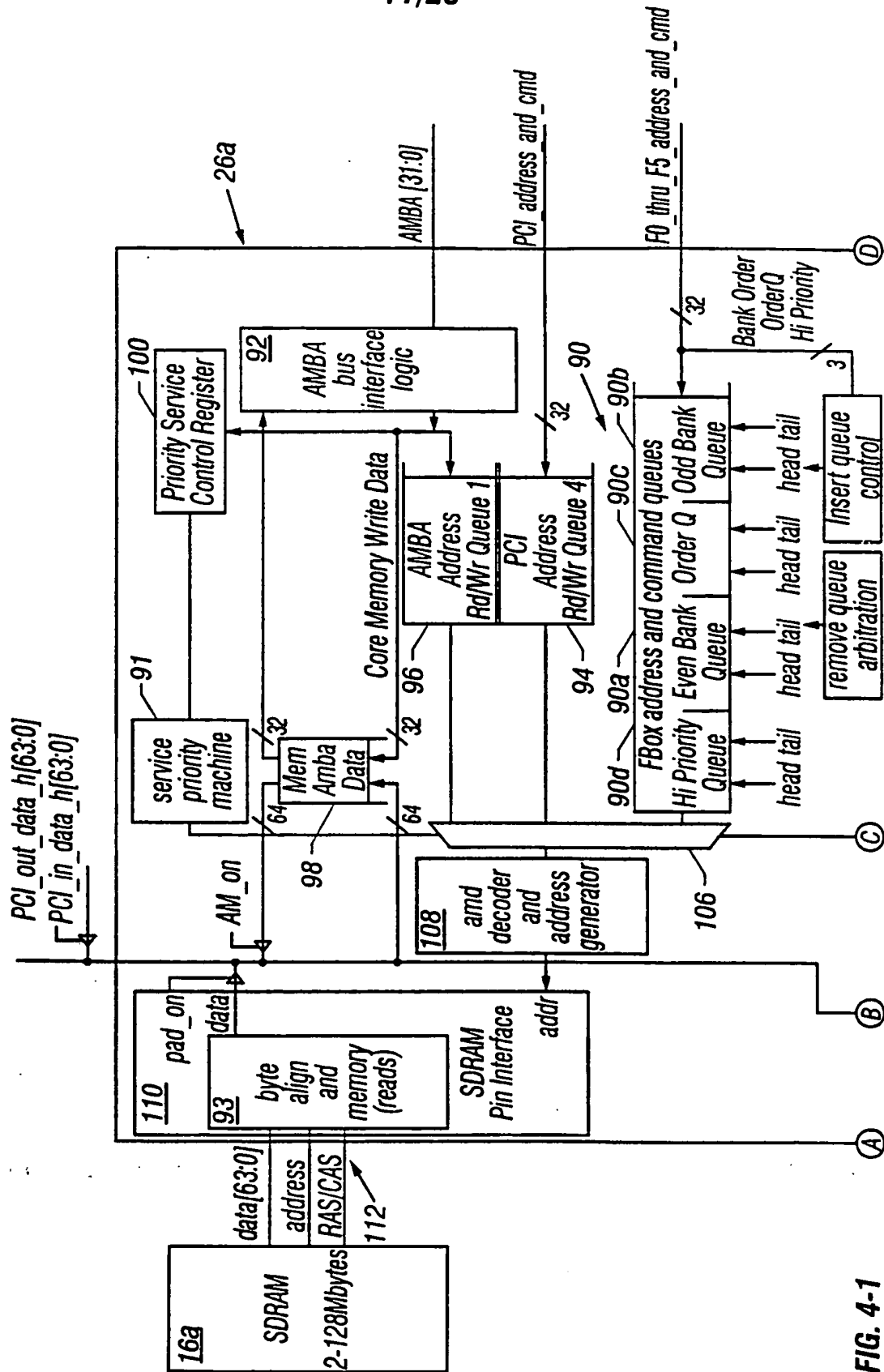


FIG. 4-1

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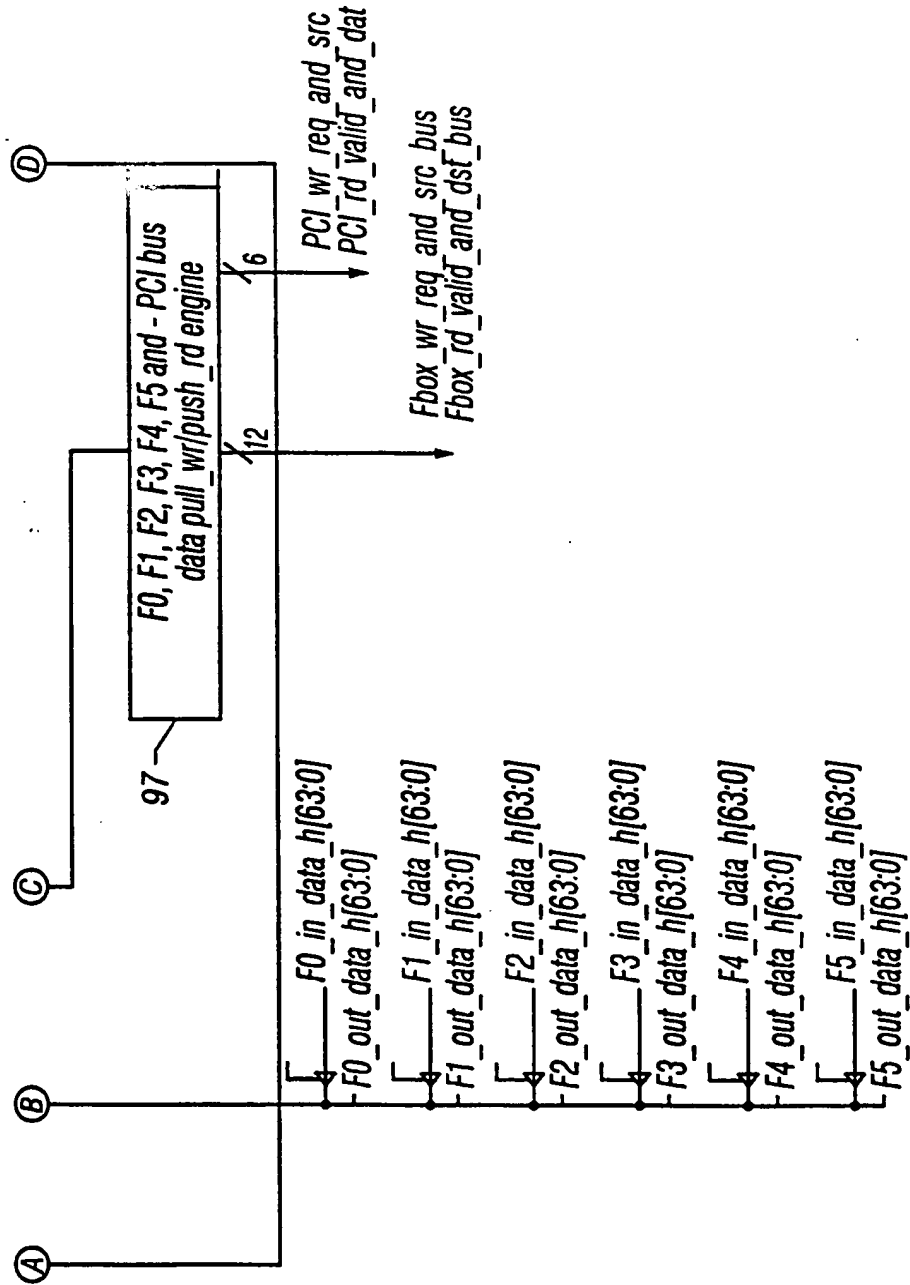


FIG. 4-2

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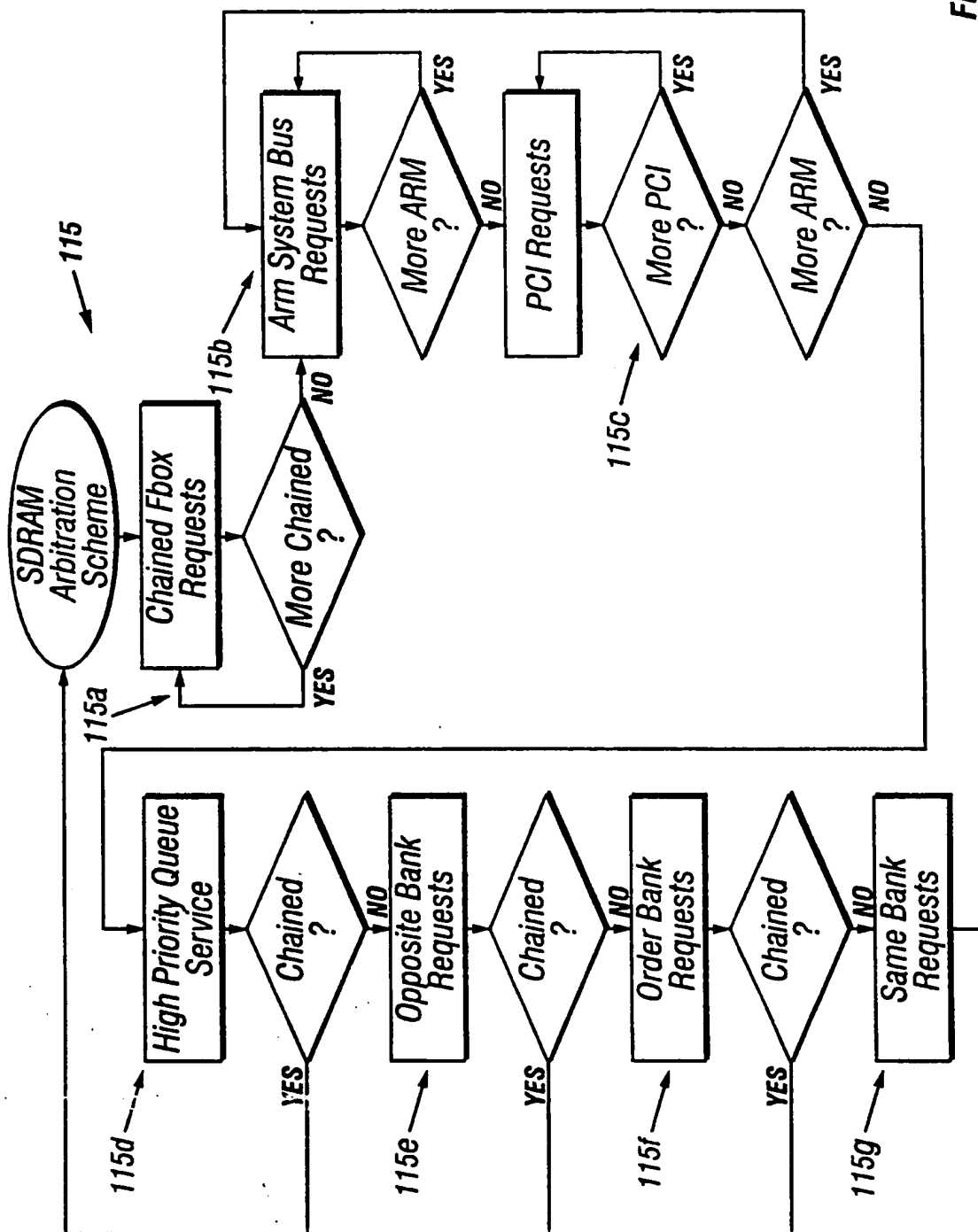
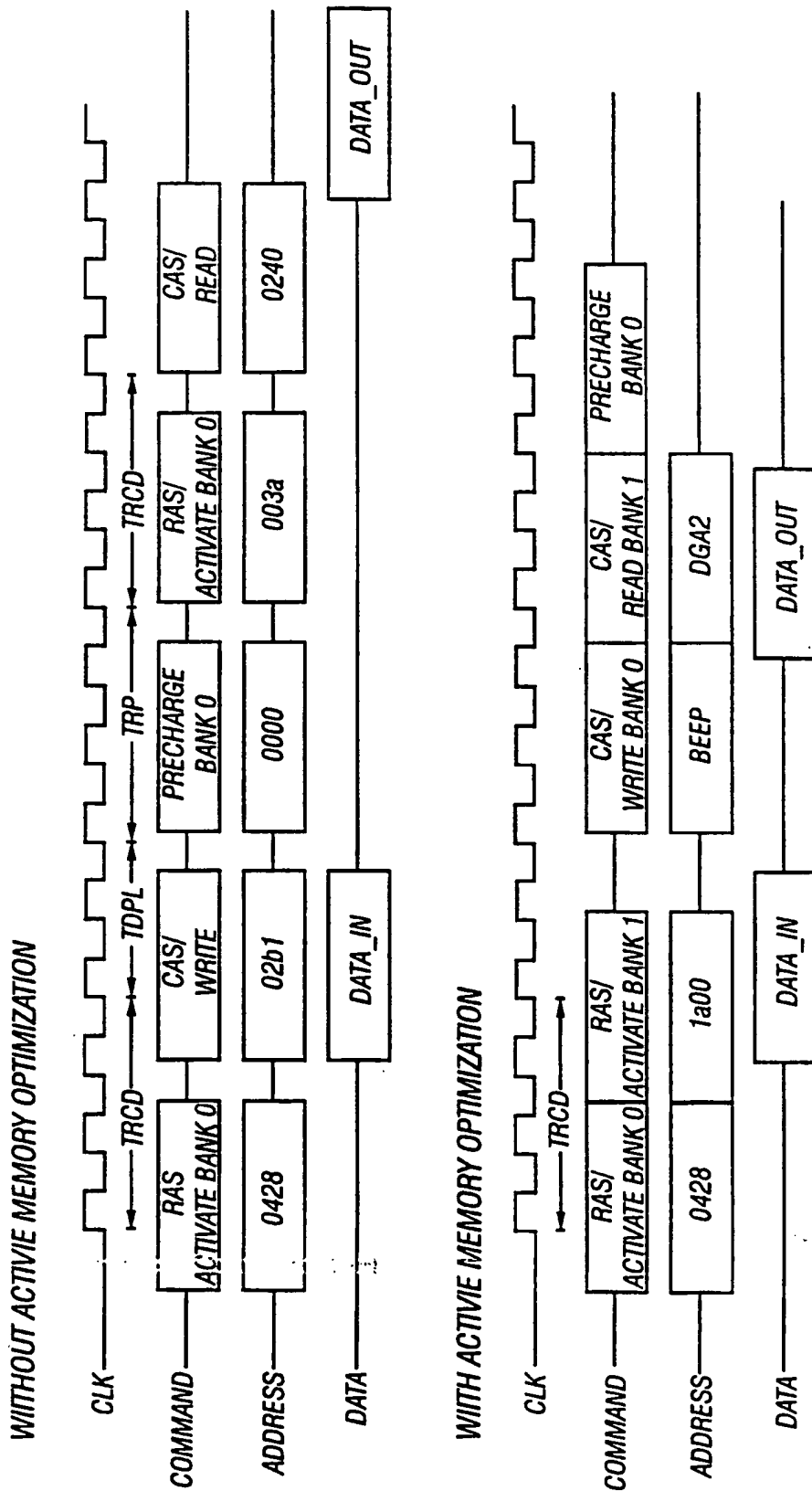


FIG. 4A

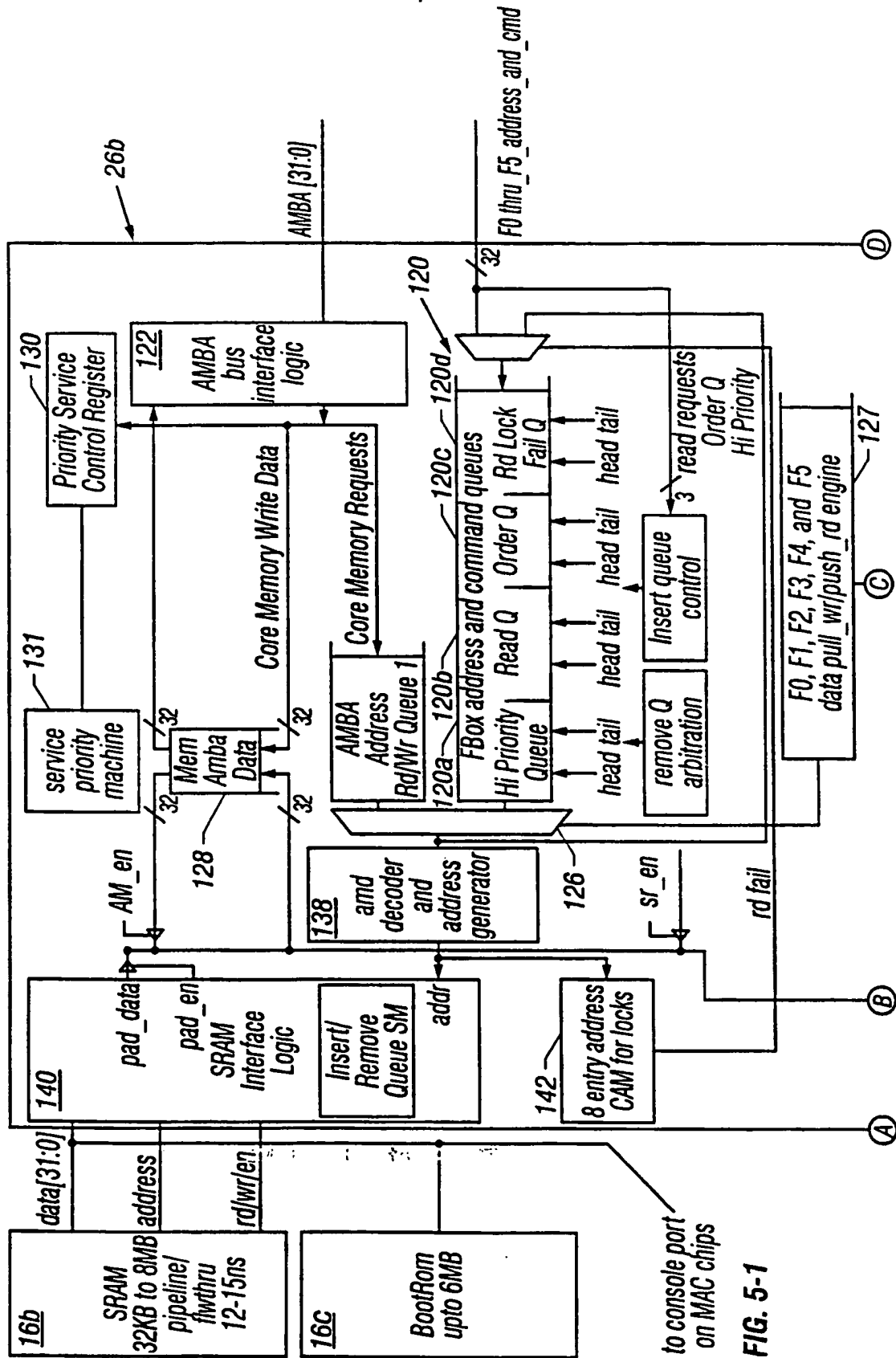
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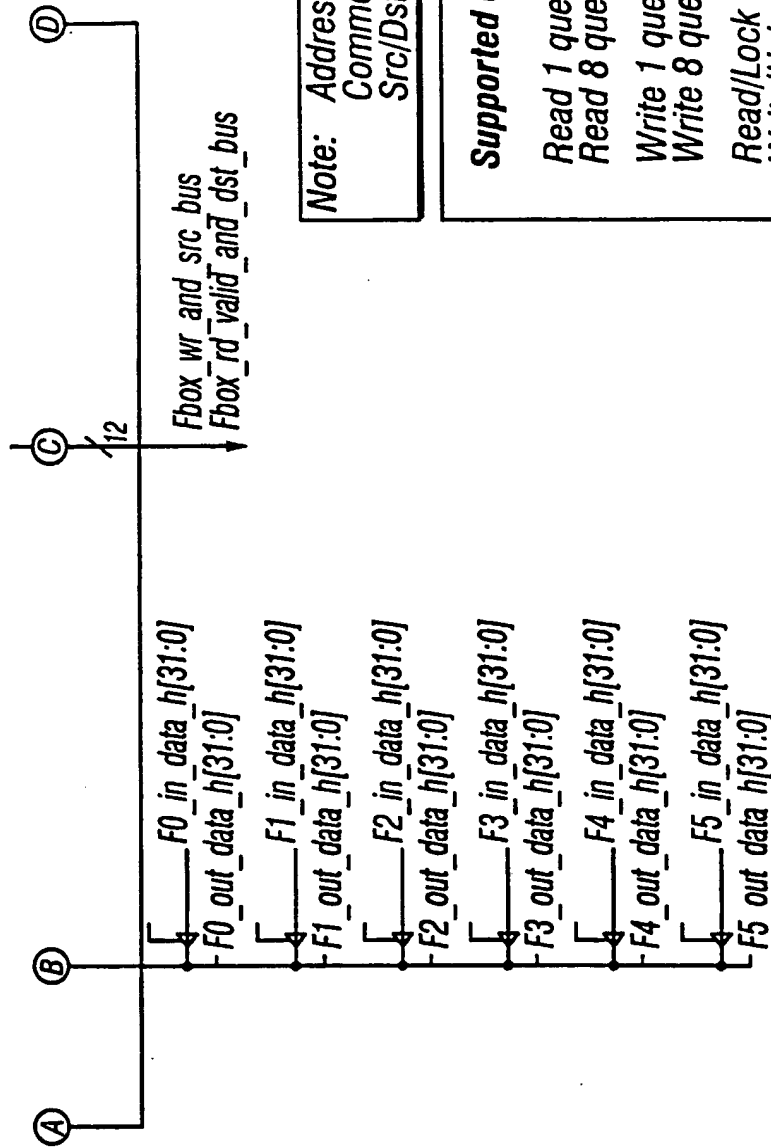
**FIG. 4B**

WHERE TRCD = RAS TO CAS DELAY  
 TDPL = DATA INPUT TO PRECHARGE DELAY  
 TRP = TIME TO PRECHARGE

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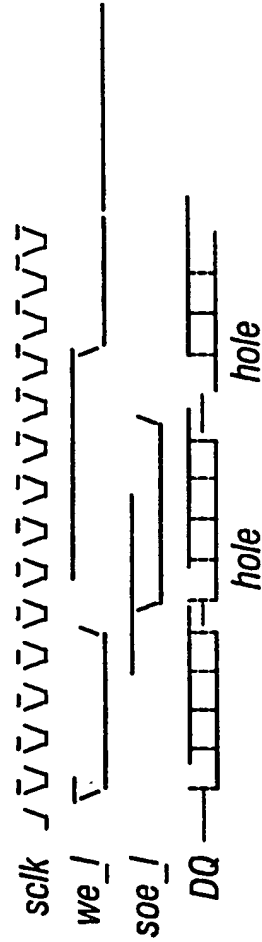
Note: Address: 22 bits  
Comment: 4 bits  
Src/Dst: 6 bits

**Supported Comments:**

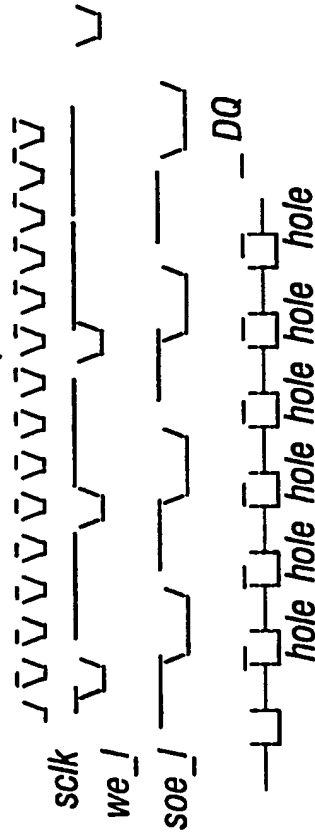
Read 1 questword  
Read 8 questwords  
Write 1 questword  
Write 8 questwords  
Read/Lock  
Write/Unlock  
Unlock  
Reserve n locks  
Insert Queue Element  
Remove Queue Element

FIG. 5-2

*4 Writes and 4 Reads followed by more reads with optimization*

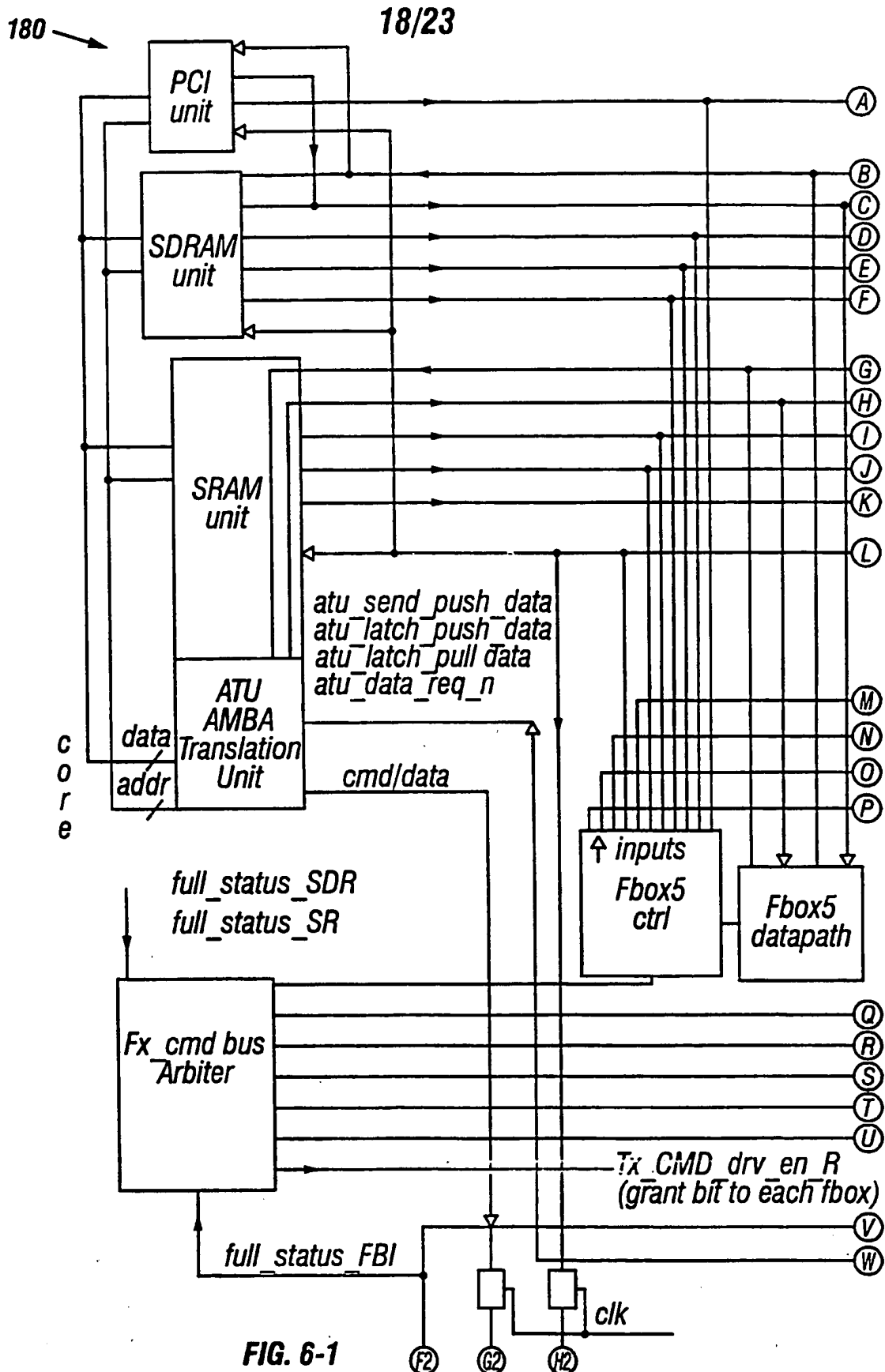


*4 Writes and 4 Reads without optimization*



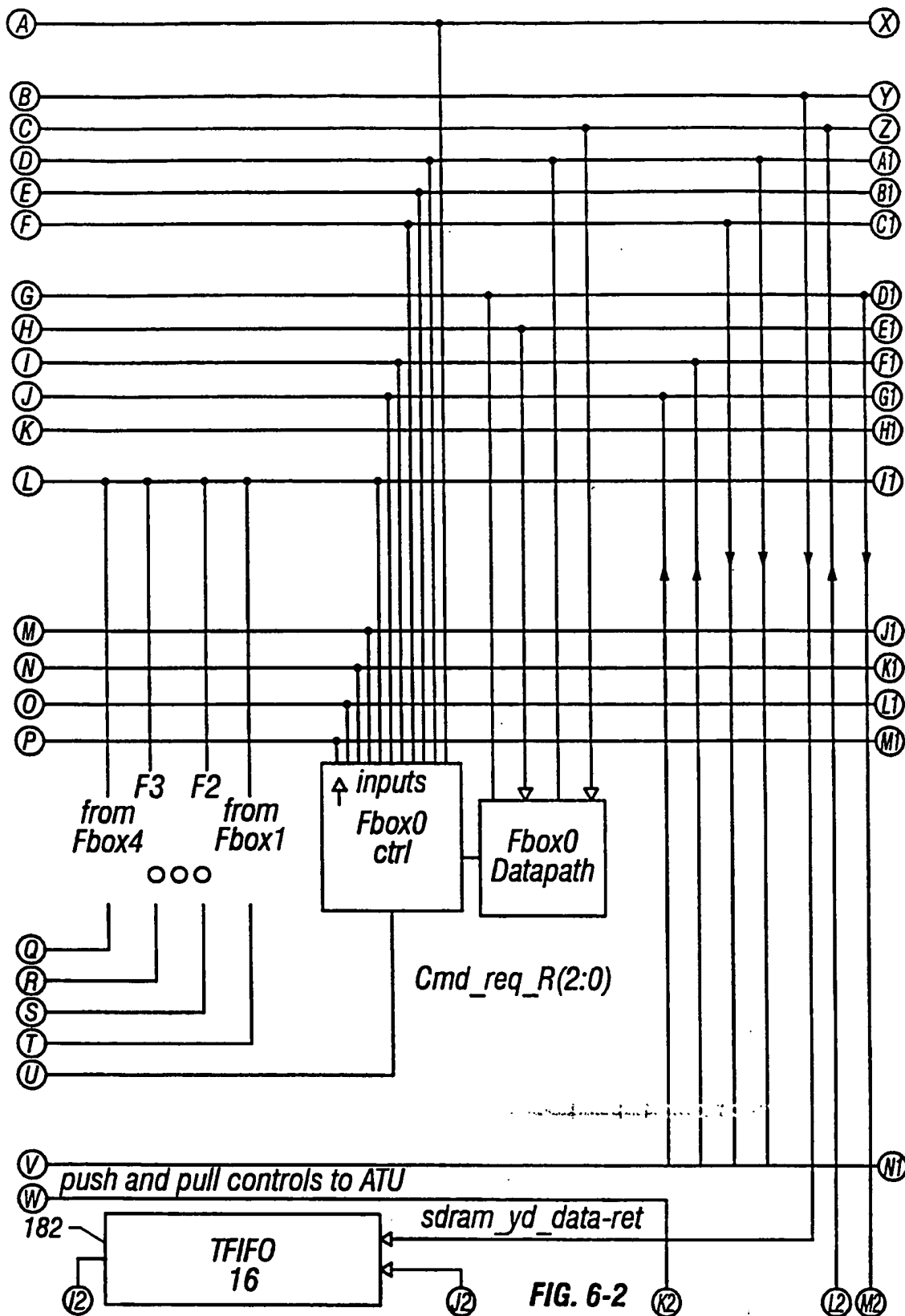
10 cycles vs. 14

FIG. 5A





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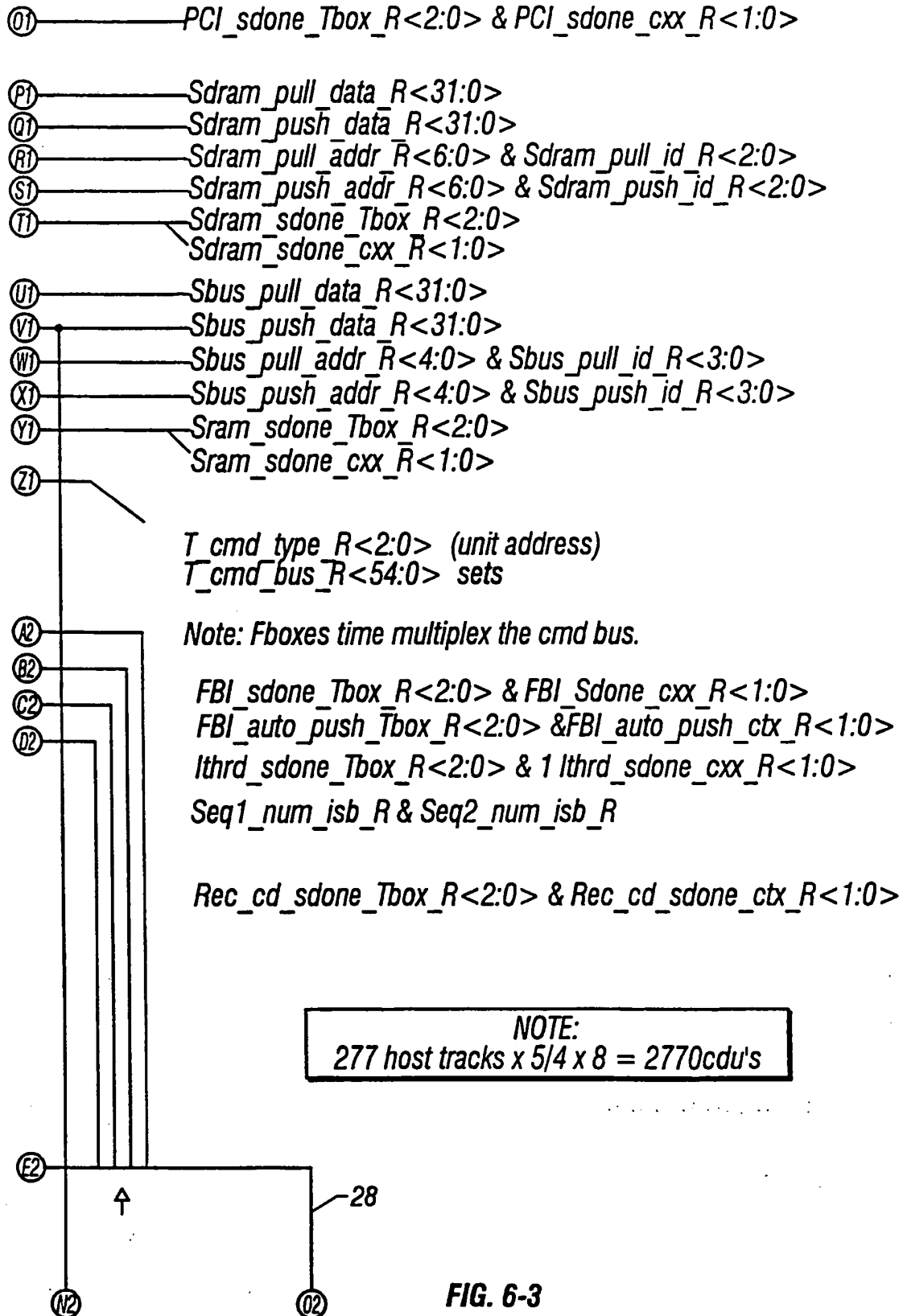


FIG. 6-3

SUBSTITUTE SHEET (RULE 26)

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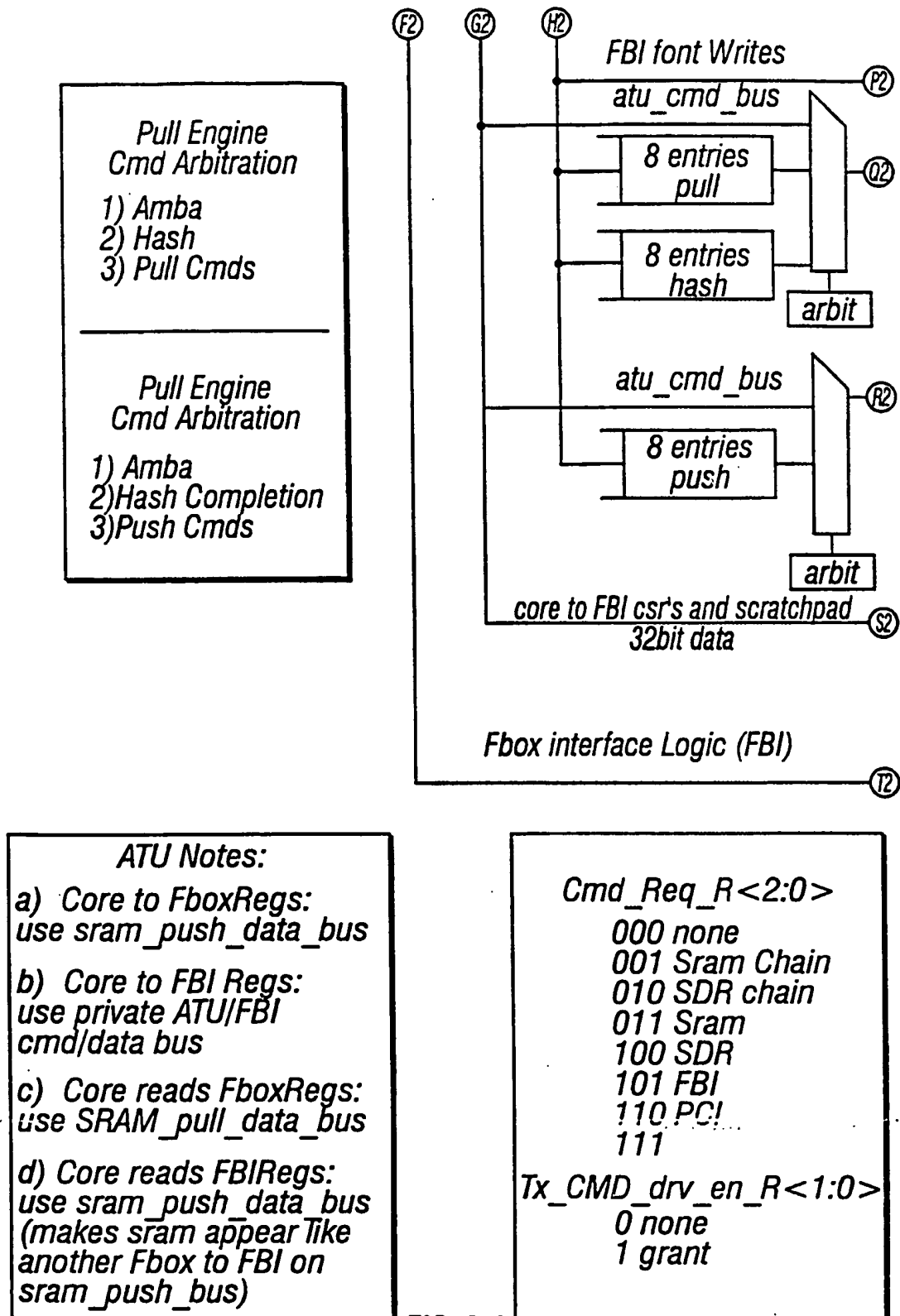
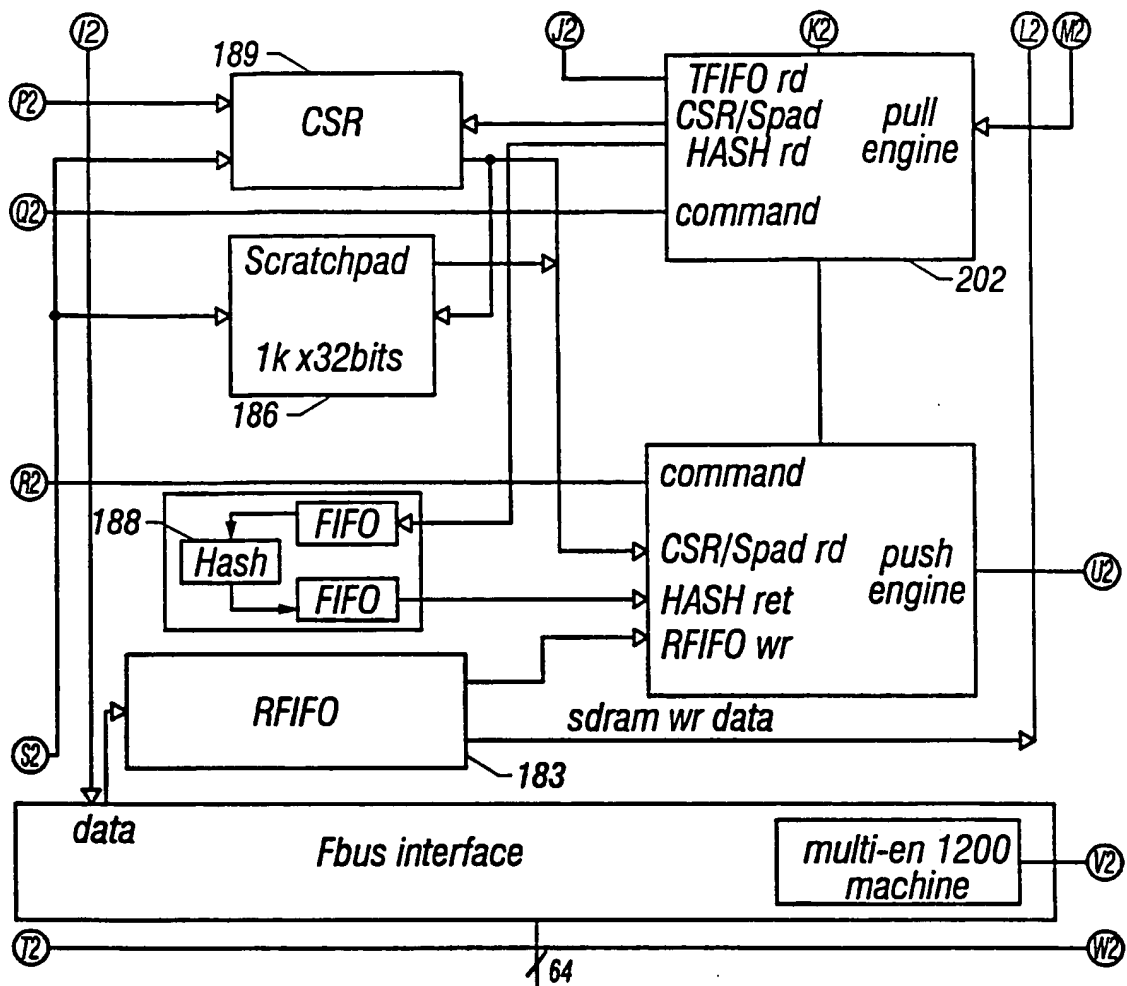


FIG. 6-4

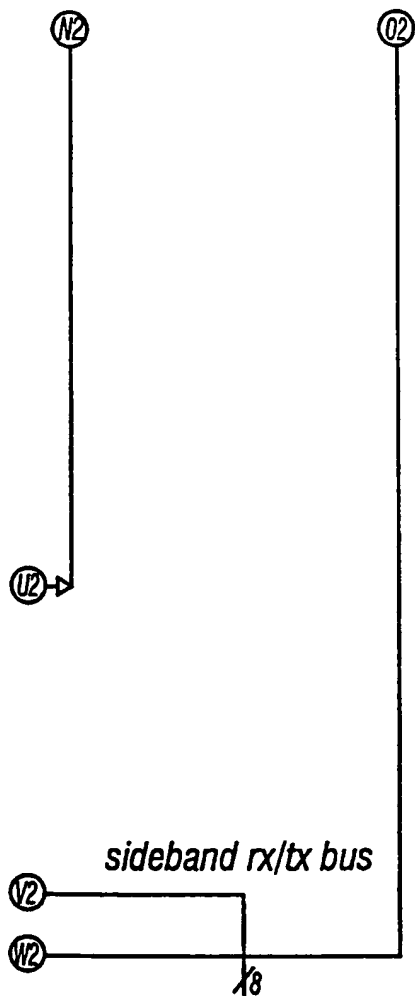
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<b>Sdram_puXX_addr_R&lt;6:0&gt;</b>	<b>Sram_puXX_addr_R&lt;4:0&gt;</b>
[4:0] xfer_reg_addr	[4:0] xfer_reg_addr
if not TFIFO	
[6:0] TFIFO_addr	
<b>Sdram_puXX_ID_R&lt;3:0&gt;</b>	<b>Sram_puXX_ID_R&lt;3:0&gt;</b>
0-5 Fboxes	0-5 Fboxes
8-13 Fboxes-csr	8-13 Fboxes-csr
6 fbi	6 fbi
15 nop	15 nop

FIG. 6-5

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<i>Fbox Branch/Ctx Choices</i>	
<i>T_Cmd_type_R&lt;2:0&gt;</i>	
000: bus idle	1) FBI_sdone <i>br / ctx</i>
001: SDRAM	2) FBI_auto_push <i>br / ctx</i>
010: SRAM	3) lthread_sdone <i>br / ctx</i>
011: SRAM-csr	4) signal_rec_cxt <i>br / ctx</i>
100: PCI	5) Seq#1_change (flag) <i>br / ctx</i>
101: reserved	6) Seq#2_change (flag) <i>br / ctx</i>
110: FBI	7) SRAM_sdone <i>br / ctx</i>
111: Scratch	8) SDRAM_sdone <i>br / ctx</i>
	9) volunteer_cxx_swap <i>ctx</i>
	10) Rec_req_available (flag) <i>br</i>
	11) SDRAM_rd_parity_en (flag) <i>br</i>
	12) Fbox_push_protect <i>br</i>
	13) ccodes, contexts and kill

FIG. 6-6

# INTERNATIONAL SEARCH REPORT

Internat Application No

PCT/US 00/22807

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 G06F13/16 G06F9/46

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, EPO-Internal, IBM-TDB, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 659 687 A (KIM ET AL) 19 August 1997 (1997-08-19) column 3, line 54 -column 5, line 61 column 6, line 62 -column 8, line 40 figures 2,3	1-18
A	US 5 905 876 A (PAWLOWSKI ET AL) 18 May 1999 (1999-05-18) column 2, line 55 -column 3, line 30 column 5, line 15 -column 6, line 3 figures 1,2	1-18
A	US 5 745 913 A (PATTIN ET AL) 28 April 1998 (1998-04-28) column 6, line 55 -column 8, line 32 figures 4,6	4-7

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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\*&\* document member of the same patent family

Date of the actual completion of the international search

19 December 2000

Date of mailing of the international search report

28/12/2000

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Authorized officer

McDonagh, F

# INTERNATIONAL SEARCH REPORT

Information on patent family members

Internal Application No

PCT/US 00/22807

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5659687 A	19-08-1997	KR 150072 B	15-10-1998
US 5905876 A	18-05-1999	NONE	
US 5745913 A	28-04-1998	NONE	